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AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Aircraft Structures Report 430

INFLUENCE OF HOLE SURFACE FINISH, CYCLIC FREQUENCY AND SPECTRUM SEVERITY ON THE FATIGUE BEHAVIOUR OF THICK SECTION ALUMINIUM ALLOY PIN JOINTS (U)

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J.Y. MANN, G.W. REVILL AND R.A. PELL

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SUMMARY

An extensive series of tests has been carried out on thick (29 mm) clearance-fit pin joints of 2L.65 aluminium alloy to investigate the effects of lug hole surface finish, frequency of cycling, spectrum severity, loading sequence and maximum load truncation on fatigue behaviour.

It was found that lug holes having a fine surface finish (1.9 microns) did not have fatigue lives greater than those with a coarse finish (27 microns), under either constant-amplitude or multi-load-level fatigue loading sequences. Thus, unless needed for other functional reasons, it may not be necessary to specify fine circumferential surface finishes in situations where fretting fatigue is likely to be a problem.

Within the range 1 Hz to 16 Hz frequency of cycling had no significant effect on the lives to failure under constant-amplitude and multi-load-level sequences.

For each of two severities of spectrum adopted (consisting of 1049 cycles per block) there were essentially no significant differences in fatigue lives under programme and pseudo-random loading sequences. Truncation of the once-per-block peak load resulted in significant reductions in life under both spectra. Detailed fractographic studies suggested that the size of the plastic zone caused by the peak load was greater than the extent of fatigue crack propagation within a block.

Fractographic examination of small fatigue cracks initiated either at intermetallics or by fretting showed no evidence of early rapid crack growth associated with the 'short-crack' effect.

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1. INTRODUCTION

The lug/pin joint connection is a common method of joining aircraft structural members which need to be disassembled for maintenance or inspection. It has been the subject of numerous fatigue investigations many of which, dealing with aluminium alloy lugs, have been summarised in Data Sheets issued by the Engineering Sciences Data Unit (ESDU) (Refs 1,2). When this type of joint is used under fatigue loading conditions, fretting between the pin and the hole surface plays a major part in crack initiation and can result in serious reductions in fatigue life.

In order to further study the fatigue behaviour of thick lugs, a comprehensive investigation was undertaken on aluminium alloy lugs of about 29 mm in thickness, with pins of 19 mm diameter. It was complementary to a previous investigation (Ref. 3) and had the objective of exploring whether the quality of hole finish was an important factor in the performance of such lugs, and whether different cyclic frequencies typical of those experienced by aircraft structures in service under gusts, manoeuvres and taxiing loads (Ref. 4) would have any significant effects on their fatigue behaviour. Consequently, the holes in the lugs were machined to provide either a 'rough' or 'smooth' finish. Fatigue tests were carried out under both constant-amplitude and multi-load-level sequences, the latter including both programme and pseudo-random loading under two load spectra of differing severity. In each case tests were made at cyclic frequencies of 1, 4 and about 16 Hz.

2. BACKGROUND

Most fatigue failures are initiated at surfaces, and irrespective of whether components enter service in the cast, forged, rolled or fully machined condition, surface finish has always been of major concern when they are subjected to fatigue loadings. The fatigue literature abounds with methods for improving the fatigue performance of the surfaces of mechanical components by using different finishing methods, heat-treatment procedures, cold-working techniques and protective treatment systems, either singly or in combination.

Forming and surface-finishing operations affect not only the surface profile (the 'smoothness' of which is usually regarded as the criterion by which a finish is

judged), but the metallurgical structure of the material in the surface layers and the residual stress system in the material (Ref. 5). In general, for the same type of external machining operation, the 'rougher' the surface profile, the worse is the fatigue performance.

Many mechanical components and structural elements are formed by the joining together of sub-assemblies with bolts and rivets. The fastener holes create regions of stress concentration and are frequently associated with the initiation of fatigue failures. However, with the development of the damage-tolerance design concept in recent years, there has been increasing concern regarding the effects of fastener hole 'quality' on fatigue life (Ref. 6), which is evidenced by both national (Ref. 7) and international (Ref. 8) evaluation programmes to study this problem.

Some of the results from the above investigations indicate that the problem of 'hole quality' is more complex than thought previously. For example, Jarfall and Magnusson (Ref. 9) have shown that for open-hole specimens (ie. those not incorporating fasteners in the holes) there is no correlation between surface roughness and the fatigue performance for holes made with the same machining technique. Other investigators (Ref. 7) have shown that fatigue performance is not adversely affected by hole roughness caused by rifling (spiral) marks, drill chatter, etc.; but that axial scratches and score marks along the length of the bore cause early crack initiation and reduced lives (Refs 7, 10). Major findings of the investigations summarised in Ref. 8 are that (in open-hole specimens) there are no significant differences in the fatigue lives obtained using high quality holes or low quality holes, and that there is no obvious correlation between the fatigue performance obtained and the cost of the hole manufacturing process.

A brief report (Ref. 11) of fatigue tests on low-load transfer specimens with various types of fasteners indicates that those embodying low-quality holes have the same fatigue behaviour as those with high-quality holes, while Jarfall and Magnusson (Ref. 9) have concluded that in such specimens the fatigue performance is influenced by the fit between the fastener and the hole rather than the hole surface finish. This finding is supported by those reported in Refs 8 and 12 where it is concluded that joints incorporating interference-fit fasteners may be relatively insensitive to the effects of hole surface finish and quality - with the exception of dimensional tolerance because of its influence on the fit of the fastener in the hole.

In joints not incorporating interference-fit fasteners, in non-friction types of bolted and riveted joints, and in pin/lug connections with clearance-fit pins where a high proportion of the load is transmitted by bearing between the shank of the fastener and the hole surface, fretting between the contacting surfaces of the hole and fastener usually accelerates the crack initiation process. The small cracks initiated by fretting are oblique to the surface (Refs 13, 14). In common with observations (Ref. 15) relating to the propagation of small non-fretting initiated cracks of less than about 0.5 mm in length, cracks initiated by fretting (for lengths of up to about 1 mm - and more particularly for lengths of 0.1 mm) have been reported to grow more rapidly than predicted on the basis of their estimated stress intensities (Ref. 16) and from macrocrack growth data. However, this small-crack behaviour is markedly affected by crack-closure effects (Ref. 17) and microstructure (Ref. 18). At greater crack lengths, continued fretting and the geometrical and stressing conditions associated with the fretting process apparently have little further influence on the propagation of the fatigue crack (Refs 13, 16) and the crack direction usually changes to be perpendicular to the surface. Fretting also causes a much greater reduction in fatigue life under low-amplitude cyclic stresses than those of high amplitude (Refs 19-21); and Edwards and Ryman (Ref. 22) have shown that the effects of fretting on fatigue strength are less under a multi-load-level sequence than under constant-amplitude loading.

Fretting is usually more apparent when the contacting surfaces have a fine finish; however, little quantitative information has been published on the effects of surface finish on fretting behaviour. That which is available suggests that surface finish either has little effect on the amount of fretting damage which develops (Refs 23, 24), or that damage decreases as the surface roughness is increased (Ref. 25). Explanations for this behaviour are that a rough surface allows the fretting debris to escape from the areas of contact into the adjacent grooves; that a rough surface provides greater opportunity for the retention of lubricants; and that some of the differential shear strains at the contacting surfaces can be accommodated by elastic deformation of the asperities (Ref. 26). Nishioka and Hirakawa (Ref. 27) have shown that surface-roughness within the range of 2 to 30 microns has no appreciable effect on the fretting strength of mild steel. However, Bilonoga (Ref. 28) has reported the fretting fatigue life of steel with a milled finish (10 to 20 microns) to be about twice that with a polished finish (0.2 to 0.3 microns). Waterhouse (Refs 13, 21)

has suggested that the effects of fretting fatigue can be minimised by roughening the surface or machining grooves on the surface; bearing in mind, nevertheless, the stress concentrations introduced by so doing. Providing that no significant degradation in fatigue properties occurs, it might be postulated that economic benefits in machining and inspection could be gained by not specifying a finer degree of surface finish than that necessary for functional reasons.

The effects of frequency of oscillation on the severity of fretting damage have formed part of several investigations (Refs 23, 25, 29, 30, 31), the first four involving steels and the last magnesium. Feng and Uhlig (Ref. 23) and El-Sherbiny and Salem (Ref. 29) have shown that between about 1 Hz and 15 Hz to 30 Hz the fretting damage decreased with increasing frequency of oscillation, while Reed and Batter (Ref. 25) reported a decrease in fretting damage in 4140 steel when the frequency was increased from 50 Hz and 100 Hz. On the other hand Soederberg et al (Ref. 30) have reported that, between the frequencies of 10 Hz and 20 kHz, the fretting wear in a low carbon steel increased with frequency, while in a stainless steel it was practically independent of frequency. Kusner et al (Ref. 31) found that the frequency of oscillation had little effect over the range 80 Hz to 290 Hz.

Much has been written on the influence of frequency of cycling on the fatigue behaviour of metals. However, most of the findings have been derived from tests on simple unnotched and notched specimens rather than from tests on joints, and thus have not incorporated the problem of fretting. For unnotched specimens tested in laboratory air at room temperature only relatively small increases in life have been reported for increasing cyclic frequencies up to about 10 Hz; but at higher frequencies the fatigue life steadily increases with increasing frequency and the rate of fatigue crack propagation is reduced (Refs 32-34). For notched specimens the cyclic frequency effects are not only more pronounced but they extend to much lower frequencies, eg. 1 Hz. Some fatigue tests at 2.5 and 17 Hz on aluminium alloy bolted joints (where the failures initiated by fretting) have indicated no significant differences in the lives to failure at the two frequencies (Ref. 35). However Endo et al (Ref. 36), as the result of fretting fatigue tests on carbon steels at 3, 10, 30 and 60 Hz, concluded that the fretting fatigue strength decreases with a reduction in cyclic frequency.

3. TESTING PROGRAMME AND RESULTS

3.1 Test material and specimens

Lug/pin joint specimens were taken from the grip portions of larger specimens used in a previous investigation (Ref. 37) which had involved two batches of extruded bars of British Standard 2L.65 aluminium alloy designated (by ARL) BJ and CL. Details of the lug/pin joint specimens are given in Fig. 1, while Fig. 2 shows the plan form of the original specimens and the locations from which fatigue, tension and compact-tension fracture toughness specimens were taken. Tension and fracture toughness specimens were, however, taken from only a small sample of the specimens. Usually, two lug/pin joint specimens were produced from each end of the original specimens. For the configuration of pin-loaded lug adopted in this investigation the theoretical stress concentration factor (nett area) is between 3.8 and 4.0 (Ref. 38). Table 1 gives the tensile and fracture toughness properties of the two batches of material.

As prior gripping of the original specimens had caused some surface damage the two faces were machined to reduce the thickness of the lug from 31.77 mm to 28.58 mm. Small chamfers were machined at each end of the lug holes. In the case of specimens used in the 'hole-surface-finish' phase of this investigation the lug holes were bored (not reamed) and two severities of surface finish were adopted - designated 'fine' and 'coarse'. Details relating to the hole machining are given in the Appendix. For the fine finish the final machining operation involved a feed of 0.033 mm/revolution and resulted in a surface finish of 1.9 microns (micrometres) Centre-Line-Average (CLA). The coarse finish was produced by a supplementary boring cut of depth 0.064 mm at a feed of 0.320 mm/revolution and this produced a surface finish of 27 microns CLA. For specimens used in the 'frequency-of-cycling' phase of the investigation the lug holes were finally fine machine-reamed to produce a surface finish of 1.9 microns CLA, the reamer being rotated as it was withdrawn from the hole.

3.2 Fatigue test conditions

All fatigue tests were carried out in an electro-hydraulic servo-controlled testing machine incorporating a 300 kN MTS actuator and control system. Figure 3

illustrates the specimen gripping system. The specimens were degreased and assembled dry - ie. without lubricants - using high-tensile steel shoulder screws as the pins and with 'Teflon' shims fitted between the specimens and the steel loading links. A slight clearance was maintained between the specimens and the links. New shoulder screws were used for every specimen. The clearances of the 'pins' in the individual holes of all specimens are included in the appropriate tables of fatigue test results. For holes having a fine finish the average clearance was 0.025 mm (0.13%), while for those with a coarse finish it was 0.026 mm (0.14%). The average clearance in the reamed holes of specimens used for the frequency-of-cycling phase of the investigation was 0.034 mm (0.18%).

Each phase of the testing programme involved constant-amplitude and spectrum-loading fatigue tests, and in all cases a constant minimum stress (on nett-area) of 23.4 MPa was adopted. Sine wave loading was used throughout and the load sequences in the spectrum-loading tests were achieved using a programmable function generator controlled by a punched tape. The load ranges in the spectrum-loading tests were those used in the constant-amplitude tests.

Two severities of spectrum were adopted. These were designated 'severe' and 'moderate' respectively and details are given in Fig. 4. All of the spectrum-loading tests in the first phase of the investigation (hole surface finish) were carried out under a low-high-low programme loading sequence as illustrated in Fig. 5. In the second phase of the investigation (frequency of cycling) some tests were also made using a pseudo-randomised sequence. The order of occurrence of individual stress cycles in the severe and moderate pseudo-random sequences are given in Tables 2 (a) and 2 (b) respectively, while Fig. 6 shows traces of one block of 1049 cycles in each case. In addition, a few tests were conducted using the pseudo-random sequence in which the once-per-block stress range coded 'F' was omitted (truncated spectrum). For the hole-surface-finish phase of the investigation the cycles with maximum stresses B to F were applied at a cyclic frequency of 1 Hz while those at maximum stress A and those with S_{max} of 44 MPa were applied at between 3 and 4 Hz. During the second phase of the investigation the particular cyclic frequency of interest was used for all stress ranges.

For the hole-surface-finish investigation the lug holes in the two individual specimens taken from the same end of the original specimen were machined to a fine and coarse finish respectively, and each particular pair of specimens were subsequently tested under the same fatigue loading conditions. The whole fatigue testing programme involved a total of nearly 150 specimens, with an average of between three and four being tested under each combination of the conditions noted above. In the hole-surface-finish phase and the constant-amplitude part of the frequency-of-cycling phase of the investigation about twice as many specimens of the BJ batch than of the CL batch were tested; whereas for the spectrum-loading part of the frequency-of-cycling phase about 85% of the specimens were taken from batch BJ.

3.3 Fatigue test results

Individual fatigue lives of the specimens tested in the hole-surface-finish phase of the investigation are given in Tables 3 and 4, while the constant-amplitude data are also presented in the S/N diagrams shown in Fig. 7. Using a least-squares analysis a third-order polynomial expression was fitted to the data to derive the average S/N curves.

The results for specimens tested under constant amplitude cycling at frequencies of 1, 4 and 16 Hz are listed in Table 5 and shown pooled on the S/N diagram Fig. 8 (a). Table 6 lists the results of specimens tested under spectrum loading at each of these cyclic frequencies.

3.4 Fracture surfaces

Figure 9 indicates the system which was used for classifying the different origins and geometries of the fatigue cracks which are given in the various Tables.

With the exception of several 'run-out' specimens, individual fatigue tests were terminated by complete fracture at one of the lug ends. The residual strength of the 'unbroken' end of each specimen was subsequently determined by loading it statically in tension through a shoulder screw in a similar manner to that in the fatigue test. For these tests the other end of the specimen was held in serrated wedge grips.

Detailed results of these tests and the analysis of the residual strength data will be covered in a separate report.

3.5 Fractographic studies of crack retardation

The influence of load truncation on fatigue crack growth behaviour was studied by a fractographic investigation (using optical and electron microscopes) on two specimens tested under the moderate spectrum and using the pseudo-random sequence. Figure 10 illustrates the fractures of specimens BJ12B4 (non-truncated, life 722.5 programmes) and BJ11J1 (truncated, 387.5 programmes). For these two specimens the ratio of lives to failure was 0.54. In the case of the non-truncated spectrum the striations produced by the maximum stress in the sequence (level 'F', 195 MPa) were used as the 'markers' for determining crack growth rates. Because of the absence of this stress level in the truncated spectrum the individual striations and repeating pattern of striations produced by the stress level 'E' of 165 MPa (which occurred 28 times per block of 1049 cycles in the non-truncated spectrum and 29 times per block in the truncated spectrum) were used as the 'markers'. Extensive use was made of a scanning electron microscope to produce a photo-montage (X2000) from which crack growth increments could be measured. However, because of the large numbers of programmes to failure, it was impracticable to obtain the crack growth characteristics over the entire length of the fatigue crack. Instead, incremental crack growth data (ie. crack growth per block) were determined for crack depths of from about 0.75 to 2.5 mm. Figure 11 presents the results of the incremental crack growth measurements.

In order to study truncation effects within an individual block of 1049 cycles, detailed scanning electron microscope examinations were made of both specimens at an arbitrary crack depth of about 2 mm. Figures 12 (a) and (b) show for each specimen (non-truncated BJ12B4 and truncated BJ11J1 respectively) the fracture markings produced by the application of one complete block at this crack depth. Measurements were made of the spacings between the striations produced by the single 195 MPa stress and those produced by each of the 28 applications of the 165 MPa stress to the non-truncated specimen, and between those corresponding to the 29 applications of this stress to the truncated specimen. Measurements corresponded to the crack front positions <u>after</u> the application of the relevant stresses.

Figure 13 was derived from the measurement of striation spacings. In Figs 13 (b) and (c) the horizontal axis has been standardised to the same scale length and represents a complete block. The vertical lines are spaced in proportion to the positions of the striations on the fracture surfaces within the particular blocks being considered, and their height represents the measured crack growth increments produced by a particular 165 MPa stress and all stresses of smaller magnitude applied between it and the 165 MPa stress which immediately preceeded it. The numerals at the top of each bar indicate the number of occurrences of stresses of 137 MPa between each successive 165 MPa stress application.

3.6 Fractographic studies of fatigue crack initiation and early growth

In order to elucidate the results regarding the effects of hole surface finish on the fatigue of lugs, detailed fractographic studies were made on each of several specimens with fine-finish and coarse-finish holes which had been tested under programme loading. Evidence was sought as to the mechanisms of crack initiation in the two cases; in particular the parts played by fretting and the stress-concentrating effects of the finish profile in initiating fatigue cracks and controlling early crack propagation. Because of the need to consider small cracks (ideally independent cracks before coalescence) with minimal damage caused by rubbing of the crack surfaces, the studies were made on the non-fatigue failure (residual strength) ends of the specimens.

Observations using a scanning electron microscope fitted with a back-scattered electron detector highlighted the presence of intermetallics in the microstructure of the alloy. Fractographic studies (Refs 5, 6, 39, 40) have shown that intermetallics and inclusions at or close to a surface can act as fatigue crack initiation sites. In the present study it was clear that the majority of fatigue cracks had initiated at either single intermetallics or at clusters of intermetallics - see, for example, Fig. 14.

For the specimens with a coarse finish, crack initiation associated with intermetallics was more obvious when they were located within the grooves than at the lands. However, in the latter case, it is likely that subsequent fretting damage may have obscured the corresponding evidence of crack initiation. Irrespective of the overall significance of intermetallics in initiating fatigue cracking, small

individual fatigue cracks were classified as to whether they had initiated within grooves (stress concentrators) or at the lands (fretting). On this basis, about 75% of the cracks in specimens with a 'coarse' hole finish were considered to have initiated because of 'geometric' stress concentrating effects, while the remainder were associated with fretting. However, because of the absence of the coarse grooves in the specimens with a 'fine' finish such a classification was not possible, nor was it possible to differentiate between cracks which had been initiated primarily by fretting or by the presence of intermetallics.

A detailed fractographic examination was made of specimen BJ20DB which had a 'coarse' hole finish and had been tested under the severe spectrum using the programme loading sequence. Thirty-five independent fatigue cracks were identified on the residual static strength end of this specimen, 19 on one side of the hole which initiated at areas of fretting at the top of the machining lands and 16 on the opposite side of the hole which initiated at intermetallic particles within the grooves (and were considered to be associated with the stress-concentrating effects of the grooves). Figure 15 shows fretting on the lands of the hole surface in the region at which the longest fretting fatigue crack initiated. The land from which this crack initiated is arrowed. The fretting on the lands at either side of the crack indicated that crack initiation had occurred at the boundary of the fretting.

Continuous crack growth information was compiled from the maximum crack depth of 2.047 mm down to a crack depth of 322 microns, and this was used to produce the crack growth curve shown in Fig. 16. At smaller depths only isolated pockets of striations were detected, some as close as 12 microns to the origin, but because of the disjointed nature of the pockets they could not be related to specific programme blocks, and thus the continuous crack growth information could not be extended back to depths of less than 322 microns. Measurements were nevertheless taken from these areas, and all of the crack growth data combined to provide a plot of incremental crack growth (per programme block) versus crack depth or the square root of the crack depth. The second relationship is presented because of the proportionality between stress intensity and the square root of crack depth in linear elastic fracture mechanics. Various representations of these data (utilizing both linear and logarithmic scales) are given in Fig. 17. Similar crack growth data were also determined for two of the cracks on the other side of the hole which initiated at

intermetallic particles or inclusions within the machining grooves. These cracks had maximum crack depths of 164 and 113 microns, and measurements of crack growth were made back to distances of 30 and 20 microns respectively from their origins. The resulting plots of incremental crack growth versus crack depth are shown in Fig. 18.

4. DISCUSSION

4.1 Fatigue data

A comparison of the constant-amplitude data obtained during the hole-surface-finish phase of the investigation (Tables 3 (a) and 3 (b)) shows that, for specimens tested at the same stress levels, the calculated values of log. average lives of specimens with coarse-finish lug holes is less than those with fine-finish holes in only one instance, ie. at S_{max} = 51 MPa. However, the differences in average lives were significant* in only two cases, namely at S_{max} = 165 MPa and 137 MPa. When all of the constant-amplitude data were pooled, a two-way analysis of variance indicated no significant difference in the lives of the specimens with fine-finish and coarse-finish holes.

In Section 3.1, reference was made to the use of two batches of test material for this and two previous investigations (Refs 3, 37). Individual groups of data in Tables 3 (a) and 3 (b) suggest that the lives of specimens from batch CL may be greater than those from batch BJ. For these hole-surface-finish constant-amplitude tests, however, any overall batch effects were minimised by pairing specimens (as indicated in Section 3.2) with coarse-finish and fine-finish holes; but this system was not maintained for the hole-surface-finish specimens tested under programme-loading with the moderate spectrum because insufficient material from batch CL was available. Although the tensile properties of the two batches are not significantly different, there is a significant difference between their values of fracture toughness - that for batch CL being greater then that for batch BJ. As in the previous investigations there is a trend for the CL specimens to be in the higher

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* All statistical comparisons were made at a 5% level of significance.

life band of each group of specimens tested under nominally identical conditions. If the assumption is made that the crack initiation and propagation characteristics of the two batches are not significantly different, then the longer lives of the CL specimens may simply reflect a larger fatigue crack before final fracture and the corresponding longer life to attain the critical size.

A comparison of the corresponding complete sets of data in Table 4 indicates that under the severe spectrum the log. average life of specimens with a coarse-finish hole is significantly greater than those with a fine-finish hole; whereas under the moderate spectrum the differences in log. average lives at not significant. However if, for both spectra, a comparison is made between specimens taken from batch BJ, only the log. average lives of specimens having coarse-finish holes are significantly greater than those with fine-finish holes. It thus appears that, in this particular instance, hole surface finish has a greater influence under multi-load-level than under constant-amplitude fatigue loading conditions. This finding is contrary to the view expressed in Reference 22 that surface finish will have less effect on fatigue under variable-amplitude loading than under constant-amplitude loading.

Nevertheless, the current findings support those summarised in Section 2 which indicated that, under fretting fatigue conditions, the use of a rough surface finish does not result in shorter fatigue lives than if a fine finish were used, and may even result in longer lives.

The constant-amplitude tests at 1 Hz, 4 Hz and 16 Hz (Table 5) indicate that, within this range of frequencies, there are no significant differences in the resulting log. average lives to failure. Furthermore, with the exception of tests at S_{max} = 51 MPa, they are not significantly different from the lives of specimens tested under corresponding conditions in the hole-surface-finish phase of the investigation, nor those reported in Reference 3. This further supports the view that hole surface finish or machining may have only a secondary effect on the fatigue lives of lugs. All of the constant-amplitude test results from both phases of this investigation were pooled to derive the S/N curve shown in Fig. 8 (b).

Table 7 summarises the results of tests under spectrum loading at the three cyclic frequencies. However, an analysis of the data shown in Table 6 for specimens

tested at 16 Hz indicated that specimens from batch CL had significantly longer lives than those from batch BJ under both the severe and moderate spectra. Thus, to provide a coherent set of data, Table 7 includes results from specimens of batch BJ only.

Under most combinations of spectra type and cyclic frequency the log. average lives increase with cyclic frequency; behaviour which is consistent with the findings from fretting tests and fatigue tests at different cyclic frequencies referred to in Section 2. However, in only one comparable case is the difference in average lives significant, namely for specimens tested at 4 Hz and 16 Hz under the severe spectrum, programme-loading conditions; and it should be noted that for both of these particular groups of specimens the standard deviations of log. life are quite small. Furthermore, the log. average lives of BJ series specimens having fine-finish holes and tested under the severe and moderate spectra respectively (Table 4), are not significantly different from those of the corresponding specimens (Table 6) which were tested at 1 Hz under programme loading. It is concluded that, between 1 Hz and 16 Hz, cyclic frequency has no significant effect on the fatigue lives of these aluminium alloy lugs.

The relative fatigue lives given in Tables 6 and 7 are an indication of the severities of the two spectra used in this investigation. For comparable testing conditions the ratios of the fatigue lives obtained under the moderate and severe spectra vary from 3.5 to 4.1 with an average of 3.7.

An assessment of the effects of loading sequence on fatigue lives can be obtained by comparing the spectrum-loading tests at 1 Hz and 4 Hz which are summarised in Table 7. In all cases, the log. average lives of specimens tested under programme loading exceeded those tested under pseudo-random loading - by up to 20%. However, in only one case - comparing groups (E) and (F) - are the differences significant. Thus, there is inconclusive evidence from these tests to assert positively that the adoption of a programme-loading sequence will result in longer fatigue lives than from a 'random' loading sequence. This is in general agreement with the findings from an investigation on the fatigue of thick-section bolted joints (Ref. 41), where it was shown that tests using a simplified programme-loading flight-by-flight sequence did not result in average lives which were significantly different than those

under a complex flight-by-flight sequence. It also supports the concept (Ref. 42) that random loading sequences can be adequately represented in many cases by block-programme sequences, providing that certain criteria relating to load levels, cycles per programme and total life to failure are met.

Truncation of the once-per-programme peak stress (195 MPa) resulted in significant reductions in life under both the severe and moderate spectra. The ratios of log. average lives (truncated/non-truncated) are 0.51 and 0.52 respectively. This is consistent with other published work (Refs 43-49) which has demonstrated the crack growth retardation effects associated with rarely occurring high loads.

Estimates (based on the simple Miner linear cumulative damage hypothesis) of the lives to failure under the severe and moderate spectra are given in Table 8. The cycles to failure at each of the stress levels A to F were obtained by pooling all of the constant-amplitude data included in Fig. 8 (b). As the Miner hypothesis does not recognize the beneficial effects of crack growth retardation, an assessment of this informatio . will be restricted to tests under the truncated spectra. Under both the severe and moderate truncated spectra the experimental lives exceed the predicted lives, the ratio of the experimental to predicted lives being 1.57 and 1.86 respectively. These results support the view expressed by Buch (Ref. 46) that, even in the absence of substantial 'crack retardation' loads, the Miner hypothesis provides a conservative estimate for the fatigue lives of lug-pin joints. The ratio of experimental lives under the two spectra is 3.72, compared with 3.14 for the predicted lives.

4.2 Fracture surface analysis

Figure 9 shows that fatigue crack development in different specimens followed a variety of patterns. However, most of the areas of cracking (at final failure) were the result of the coalescence of numerous smaller cracks. In the majority of cases cracks did not initiate exactly on the plane of minimum section.

Under constant-amplitude conditions, fatigue crack development was usually initiated by fretting within the hole but close to the chamfers at the ends. This was not unexpected because of the lug geometry (high values of t/d) and the influence of

pin bending (Ref. 50). There were few other initiation sites. At the higher stress levels crack initiation usually occurred from all four corners, but at the lower stresses crack development from only one or two corners was more common. In nearly all the constant-amplitude tests the subsequent crack development produced shapes approximating to quarter-elliptical corner cracks.

Crack initiation and development in specimens tested under spectrum loading was different to that under constant-amplitude in that there was a much greater prevalence of progressive multiple crack initiation along the bore of the hole leading to an irregular crack front shape which approximated to a semi-circular embedded crack - see, for example, specimens tested at 4 Hz under the moderate spectrum (Table 6). Similar crack development during multi-load-level tests was observed previously (Ref. 3) and attributed to the high loads in the spectrum sequence successively causing gross slip after periods of 'stable' fretting conditions under the lower loads, resulting in the progressive re-initiation of fretting conditions further along the hole. This concept has recently been confirmed by Soederberg et al (Ref. 30) who concluded that, in high amplitude fretting, gross slip occurs at the interface and wear is the dominant mode of damage, whereas at low amplitudes fretting is more likely to cause smaller scale surface degradation and fatigue crack initiation. Nevertheless, intermetallic particles play an important role in the initiation of fatigue cracks in aluminium alloys because of their stress concentrating effect in the matrix, and the introduction of discontinuities associated with particle fracture and particle/matrix debonding. Thus, the actual sites at which progressive fatigue crack initiation along the hole occurs may be closely associated with the fracture behaviour of specific intermetallic particles in the matrix near the surface of the hole.

4.3 Crack retardation

Figure 11 shows that, for all crack depths at which measurements were made, the growth rate per programme is greater for the specimen tested under the truncated spectrum than that tested under the non-truncated spectrum. At small crack depths (eg. 0.75 mm) the ratio of crack growth rates is about four, decreasing to a value of about two at a crack depth of 2.25 mm. At larger crack depths the ratio might be expected to further decrease. Thus, although no information was

obtained as to the relative lives to fatigue crack initiation under the two spectra, the differences in crack propagation rates are not inconsistent with differences in total lives to failure of about two.

Figure 13 also clearly shows that the crack growth per programme block is much greater in the truncated case. It can be seen from Fig. 13 (c) that there is an approximate correlation between each particular crack growth increment and the number of applications of the 137 MPa stress in the preceding interval. In general, three or more applications of the 137 MPa stress produce an increment of growth greater than 1.0 micron, while two or less produce increments of less than 1.0 micron. A comparison of Figs 13 (a) and (c) shows that both the total crack growth per programme and that associated with each corresponding application of the 165 MPa stress is considerably greater under the truncated spectrum. However, a comparison of Figs 13 (b) and (c) shows that while the magnitude of the cracking is markedly different in each case, the relative positions of the striations are almost identical. The only major difference is the distance between the second last and last measurements, which is much greater in the non-truncated case because the last measurement includes the relatively large increment of growth associated with the single application of the highest stress of 195 MPa.

It should be noted (see Table 2 (b)) that under the pseudo-random sequence the relative numbers of applications of each of the levels less than 165 MPa occurring between each successive application of the 165 MPa stress are not constant. It would appear that the once-per-block 195 MPa stress application caused subsequent crack retardation, and that its effect extended beyond the overall crack growth in one programme block. On the assumptions of an embedded semi-circular crack of 2 mm in depth (equal to the depth at which the relevant crack growth measurements were made - see Fig. 13), estimates were made of the size of the plastic zone produced by this load. The radius of the plastic zone (r_p) under plastic strain conditions was firstly calculated using the following commonly used expression (Ref. 51) :

$$r_p = 1/6\,\pi\,(K_I^{\,2}/\sigma_y^{\,2})$$

where the stress intensity (K_I) at the deepest part of the crack was calculated using the analysis in Ref. 52, and σ_y taken as 457 MPa. The resulting value of r_p was 52

microns. Secondly, a value of 0.33 for Poisson's ratio was assumed and the radius of the plastic zone calculated from the more exact expression (Ref. 51) :

$$r_p = (1-2\nu)^2 \ (1/2\pi) \ (K_I^{\ 2}/\sigma_y^{\ 2})$$

This gave a value of 18 microns for r_p. Both of these estimated values of r_p exceed the crack growth increment of approximately 12 microns between successive applications of the 195 MPa stress in the non-truncated spectrum determined from fractographic measurements (Fig. 13 (b)) at a crack depth of 2 mm. This provides support for the concept that throughout this crack growth increment any further plastic deformation associated with lower loads and any crack extensions caused by them would be occurring in a region subjected to retardation caused by the last prior application of the non-truncated load. It is therefore not surprising that, while the magnitudes of the incremental crack growth are different, the relative measured positions of the striations produced by successive applications of the second-highest stress (165 MPa) are similar in specimens tested under each of the non-truncated and truncated spectra.

Reference to Table 8 indicates that, using the simple Miner analysis, the stresses of 137 and 105 MPa account for about 33% and 28% respectively of the total damage of the spectrum and that the damage contribution of the 67 and 51 MPa stresses is negligible. However, the fractographic investigations were not pursued deeply enough to obtain experimental confirmation of crack growth under these lower load levels.

4.4 Fatigue crack initiation and early growth

From Fig. 17 it can be seen that for the fretting fatigue crack, the growth rate slowly increased up to a depth of about 0.200 mm but then increased approximately linearly with increasing depth. Figure 19 combines all of the data in Fig. 18 with that for a crack depth of up to about 0.15 mm from Fig. 17. This indicates that at small crack depths the propagation rate for the fretting-induced crack is substantially the same as that for the two small cracks on the other side of the hole which were not initiated by fretting.

During the early stages of crack development it has been postulated by Moon (Ref. 53) for non-lubricated lug-pin joints, and shown by others for fretting-induced cracks (Refs 16, 54, 55) and short fatigue cracks (Ref. 15), that during this period crack growth rates are much faster than those which occur when the cracks are somewhat longer. If this had been the case in the present investigation, the small fatigue cracks would not have demonstrated a continuous increase in propagation rate with crack depth, nor would the growth rates for longer cracks have increased monotonically with depth. The absence of the short crack effect has also been reported by Forsyth and Powell (Ref. 56) for cracks which developed at fastener holes in 7050 and 7010 aluminium alloys under a variable-amplitude loading sequence, and by Potter and Yee (Ref. 57) after studying cracks emanating from holes in bolted joint specimens of 7475-T7651 plate tested under a flight-by-flight sequence. Differences in the behaviour of short cracks either demonstrating or not demonstrating rapid early crack growth can be clearly recognized by plotting the data as shown in Fig. 17 (c). If relatively rapid growth at short crack lengths is occurring the crack propagation rate will (as shown by Sato and others (Ref. 54), Le May and Cheung (Ref. 58)) clearly indicate (initially) a decreasing rate of growth to a minimum value followed by an increase in rate corresponding to long-crack behaviour. It should be noted at this stage that most of the published work which has supported the observations of faster crack propagation rates for cracks of very short length compared with those at longer lengths have been based on fatigue tests under constant-amplitude loading conditions.

As is typical of fretting-induced fatigue cracks, early growth was at an angle of approximately 45° to the surface of the hole (Refs 16, 55, 59, 60). The plane of subsequent crack development is normal to the loading direction and occurs when the crack propagates into the region beyond the influence of the fretting stresses (Refs 13, 16). The initial growth region was approximately 180 microns deep, about equal to the depth over which the slow crack growth was measured. As the observations in the scanning electron microscope were made perpendicular to the plane in which the major crack growth occurred (ie. greater than about 200 microns), there would have been an optical foreshortening of the plane corresponding to the initial stages of crack growth - a non-planer problem which has been discussed by Underwood and Starke (Ref. 61). The crack growth measurements were therefore corrected to compensate for this foreshortening by dividing the initial distance between the origin

and each of the programme marking by Cos 45^{o} - effectively increasing the previously measured distance from the origin to each marking by 40%. As shown by comparing Figs 20 (a) and (b) this procedure (for small cracks) extended the apparent distance over which slower crack growth was observed by 40%, but did not change the rate of crack growth in this region as both the incremental crack depth and the total crack depth were equally influenced by the correction. Basically, as shown by comparing Figs 20 (c) and (d), it resulted in a slight displacement of the relevant points upward and to the right relative to the equivalent points for the uncorrected data, but still does not suggest early rapid growth rates for short cracks.

5. CONCLUSIONS

1. In thick aluminium alloy pin joints, the fatigue lives of lugs with holes having a fine surface finish (1.9 microns) were not greater than those having a coarser finish (27 microns), under either constant-amplitude or multi-load-level fatigue loading sequences. In most cases the lives were less.

2. It follows that, unless for other functional reasons, it may not be necessary to specify fine circumferential surface finishes in situations where fretting fatigue is likely to be a problem.

3. Within the range 1 Hz to 16 Hz, cyclic frequency had no significant effect on the lives to failure of comparable lug specimens tested under constant-amplitude and multi-load-level sequences.

4. For each of the two severities of spectrum used in the investigation (consisting of 1049 cycles per block), there were essentially no significant differences in fatigue lives under programme ana pseudo-random loading sequences.

5. Truncation of the once-per-block peak stress resulted in significant reductions in life under both spectra. This was attributed to the size of the plastic zone caused by the peak stress being greater than the extent of fatigue crack propagation within a programme block.

6. Intermetallic particles were a major source of fatigue crack initiation, either alone or associated with surface fretting.

7. Fractographic examination of small fatigue cracks initiated either at intermetallics or by fretting under multi-load-level sequences showed no evidence of early rapid crack growth commonly observed with short cracks under other circumstances.

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APPENDIX - Machining of lug holes

A. "Surface finish" specimens

1. Holes drilled to approximately 1.5 mm under finished diameter.

2 (a) Fine finish:

(i) Holes rough bored to 18.885 ±0.013 mm diameter.

(ii) Holes fine bored (feed 0.033 mm/revolution) to 19.012 ±0.013 mm diameter.

2 (b) Coarse finish:

(i) As above.

(ii) As above.

(iii) Holes coarse bored (feed 0.320 mm/revolution) using a cut of depth 0.064 ±0.013 mm.

3. Hole boring details.

(i) Type of boring bar - high speed steel.

(ii) Form of cutter - 90^{0} vee, positive rake, tip radius 0.127 mm.

(iii) Cutting speed - 21 300 to 30 500 mm/minute.

(iv) Cutting fluid - kerosine.

B. "Frequency of cycling" specimens.

1. Holes drilled to approximately 1.5 mm under finished diameter.

2. Holes machine-reamed to 19.012 ± 0.013 mm diameter.

C. Surface finish measurements.

Surface finish measurements were made as specified in British Standard 2634 Part 1, 1974 in each hole of four fine-bored, four coarse-bored finish and four reamed-hole specimens. A stylus traversing length of 4 mm was used with a meter cut-off of 0.8 mm. The average values obtained were :

Fine bored finish, 1.9 microns CLA.
Coarse bored finish, 27 microns CLA.
Fine reamed finish, 1.8 microns CLA.

TABLE 1 (a)

Tensile properties of material

Material batch	No. of tests	0.1% PS (MPa)	0.2% PS (MPa)	UTS (MPa)	Elong. (% on 51 mm)	0.1% PS / UTS
Specification BS L.65 (minimum)		432	-	494	8	[0.87]
BJ	25					
Average		457	463	510	11.5	0.90
Stand. deviat.		12	13	10	1.0	
Coeff. variat.		0.026	0.028	0.019	0.081	
CL	12					
Average		469	476	526	12.0	0.89
Stand. deviat.		9	9	6	1.0	
Coeff. variat.		0.019	0.019	0.011	0.076	

TABLE 1 (b)

Fracture toughness of material

Material batch	Number of tests	K_{Ic} (MPa.m½)	
BJ	7	Average	25.9
		Stand. deviat.	0.4
		Coeff. variat.	0.016
CL	7	Average	30.9
		Stand. deviat.	0.5
		Coeff. variat.	0.015

TABLE 2 (a)
Severe spectrum, pseudo-random sequence.
Order of occurrence of 1049 individual stress cycles

C	B	B	D	C	D	C	C	D	B	C	E	A	D	C	B	C	A	B	B	C
C	E	B	D	A	E	D	D	C	B	B	C	C	A	E	B	C	C	C	C	C
C	D	B	C	D	E	C	D	D	C	C	C	C	A	B	A	D	B	E	D	A
C	C	B	C	C	C	B	C	E	D	D	B	B	B	C	D	B	D	D	C	C
B	B	C	D	B	D	B	B	C	B	D	E	B	B	D	C	E	D	D	C	B
D	D	C	B	D	D	A	C	D	C	C	B	B	C	D	D	D	C	D	B	C
C	B	C	B	D	D	D	D	C	A	D	B	A	E	C	E	D	D	A	C	D
C	C	B	C	A	D	B	C	B	D	C	B	C	B	C	C	A	B	A	C	B
D	C	A	A	D	D	D	B	C	E	C	C	C	C	C	A	C	D	C	D	E
B	B	B	E	B	D	C	B	E	D	B	B	B	C	B	E	D	C	C	C	C
C	C	D	D	B	C	B	C	D	C	C	C	E	C	C	E	C	B	B	D	C
B	E	D	A	A	C	C	C	D	B	B	B	C	D	B	D	D	A	E	D	C
B	D	D	E	D	D	E	E	C	B	C	C	D	E	B	B	D	C	D	C	B
D	C	A	D	C	D	B	D	C	B	D	C	D	B	B	E	D	B	E	C	D
B	C	E	B	C	B	B	C	B	A	B	B	A	B	D	C	A	D	B	B	D
A	E	E	C	D	B	B	C	C	B	B	C	C	D	C	C	C	B	B	C	C
D	C	D	E	C	D	E	C	C	B	B	B	C	D	B	D	B	D	D	E	D
E	C	D	D	B	D	A	D	C	A	D	C	B	D	D	B	B	C	E	B	C
C	C	B	C	A	D	C	C	B	B	D	D	B	B	D	B	C	D	D	A	B
C	B	C	B	D	D	B	D	D	C	B	A	C	E	E	D	C	E	B	C	C
E	B	D	A	A	E	B	C	E	B	C	C	C	C	E	C	D	B	E	D	D
C	C	B	B	D	B	D	D	C	D	C	D	B	A	B	B	C	C	B	B	C
D	E	B	E	B	D	D	D	A	D	D	B	E	B	B	B	C	B	C	C	B
D	C	B	C	E	B	B	B	A	E	C	B	D	B	C	E	C	C	C	D	C
B	C	B	D	D	C	C	C	B	B	E	D	B	B	B	C	B	C	B	B	E
F	D	C	B	D	E	B	B	B	B	A	D	B	C	C	D	C	A	C	A	B
B	E	D	D	D	C	D	E	E	B	C	B	C	D	A	B	A	B	C	B	C
C	C	B	D	A	C	C	B	D	C	C	D	B	B	C	E	C	B	C	C	B
B	C	B	C	C	C	B	C	C	C	B	D	B	E	C	B	B	A	C	B	D
C	D	D	E	E	D	E	D	B	C	D	B	C	E	D	D	C	E	D	C	D
D	C	C	C	E	A	C	B	E	B	B	C	C	D	C	C	B	B	B	B	B
B	D	D	E	C	B	D	C	E	C	E	B	C	C	D	B	C	B	C	D	C
D	E	B	E	C	E	D	A	C	B	D	C	D	D	B	E	D	E	E	E	C
D	C	A	B	C	C	D	B	D	E	C	C	B	B	E	D	D	B	E	A	C
D	E	B	D	D	C	E	D	D	B	A	B	D	D	C	C	C	B	D	B	E
B	C	C	B	B	B	E	E	D	A	B	C	D	C	E	C	E	C	C	E	C
B	D	C	A	B	B	C	B	D	E	D	C	E	B	C	A	D	B	A	D	C
B	C	B	D	B	C	D	E	D	B	C	B	B	C	B	D	C	C	E	E	A
C	D	C	E	C	C	C	D	D	C	D	D	B	C	B	D	C	C	B	B	C
D	B	C	A	C	E	C	B	B	C	B	B	A	D	B	B	B	B	E	C	A
D	B	C	B	D	C	B	D	B	B	C	D	B	B	B	D	B	B	E	D	E
E	C	C	C	D	C	C	B	B	E	D	C	D	C	B	D	B	C	D	D	B
E	E	B	B	C	B	B	D	B	D	B	D	A	C	E	B	B	E	B	D	B
A	B	D	C	A	E	D	D	B	B	D	B	B	E	D	E	E	C	B	C	B
E	D	C	B	A	C	C	B	C	B	B	A	B	E	D	E	B	C	D	C	C
C	B	C	B	B	B	B	B	D	C	C	C	C	D	E	B	B	B	C	C	B
C	B	C	D	D	C	B	D	A	D	C	A	E	C	B	B	A	C	A	C	C
D	A	B	B	D	A	D	B	C	C	C	B	D	D	B	D	D	D	C	C	C
B	D	D	E	B	C	D	B	B	B	B	B	D	D	C	E	B	B	B	A	D
D	D	B	C	B	D	B	D	C	D	D	C	E	B	A	D	B	B	A	A	

For order of occurrence read downwards; each column in succession.

TABLE 2 (B)
Moderate spectrum, pseudo-random sequence.
Order of occurrence of 1049 individual stress cycles

B	A	A	B	B	B	B	A	B	A	B	E	A	C	A	A	A	A	A	A	B
B	C	A	C	A	D	C	B	B	A	A	B	B	A	E	A	B	B	B	A	B
B	B	A	B	C	D	A	B	B	A	B	B	B	A	A	A	B	A	D	C	A
B	A	A	B	B	B	A	A	D	B	C	A	A	A	B	C	A	C	C	A	B
A	A	B	C	A	C	A	A	B	A	B	D	A	A	B	B	C	B	B	B	A
B	C	A	A	B	B	A	A	B	B	B	A	A	B	C	B	B	B	B	A	B
B	A	B	A	B	B	C	B	B	A	C	A	A	E	A	E	B	C	A	B	C
B	A	A	B	A	C	A	B	A	C	B	A	A	A	B	B	A	A	A	A	A
B	A	A	A	C	C	B	A	B	E	B	B	B	A	B	A	A	B	A	C	D
A	A	A	D	A	B	A	A	E	B	A	A	A	A	A	D	B	B	B	B	A
B	B	B	C	A	B	A	B	B	A	B	A	E	B	B	C	A	A	A	B	B
A	D	C	A	A	B	B	B	B	A	A	A	B	C	A	C	C	A	D	B	A
A	B	C	D	B	C	E	D	A	A	A	B	B	D	A	A	B	B	C	B	A
B	A	A	C	B	C	A	B	B	A	B	B	B	A	A	D	B	A	D	A	B
A	B	E	A	B	A	A	B	A	A	A	A	A	A	B	B	A	C	A	A	C
A	D	D	A	B	A	A	A	A	A	A	B	A	C	A	A	B	A	A	B	B
C	A	B	D	B	C	E	A	B	A	A	A	A	B	A	C	A	B	C	E	C
D	B	C	C	A	C	A	B	A	A	C	A	A	C	B	A	A	A	C	A	B
A	A	A	B	A	B	B	B	A	A	B	C	A	A	B	A	A	C	B	A	A
B	A	A	A	C	C	A	C	C	B	A	A	A	D	D	B	B	D	A	A	B
E	A	C	A	A	D	A	B	E	A	B	B	B	B	C	B	C	A	E	B	B
B	A	A	A	B	A	C	B	A	B	B	B	A	A	A	A	B	A	A	A	A
C	E	A	D	A	C	C	B	A	C	C	A	D	A	A	A	B	A	A	B	A
B	B	A	A	D	A	A	A	A	D	B	A	C	A	A	D	B	B	B	C	A
A	A	A	B	B	A	A	B	A	A	D	B	A	A	A	A	A	A	A	A	E
F	C	B	A	B	E	A	A	A	A	A	B	A	B	A	B	A	A	B	A	A
A	D	C	B	C	B	B	D	E	A	A	A	A	C	A	A	A	A	A	A	A
A	B	A	B	A	B	B	A	B	B	B	C	A	A	B	D	B	A	B	A	A
A	A	A	A	B	B	A	B	B	A	A	B	A	C	A	A	A	A	B	A	B
B	B	C	D	D	B	D	C	A	A	C	A	B	C	B	C	A	D	C	B	C
C	A	B	A	D	A	B	A	E	A	A	B	A	B	A	B	A	A	A	A	A
A	B	B	D	A	A	B	B	E	A	C	A	A	A	C	A	B	A	B	B	A
B	D	A	D	B	C	B	A	A	A	B	B	B	B	A	C	B	E	D	E	B
C	A	A	A	B	A	B	A	C	D	B	A	A	A	D	B	C	A	C	A	A
C	C	A	B	C	A	D	C	C	A	A	A	C	C	B	B	B	A	B	A	C
A	B	B	A	A	A	E	C	C	A	A	B	B	B	E	B	C	B	A	E	A
A	C	A	A	A	A	B	A	B	C	C	A	C	A	B	A	C	A	A	C	B
A	A	A	C	A	B	B	D	B	A	B	A	A	B	A	C	B	A	D	D	A
B	C	A	C	B	A	A	C	B	B	B	B	A	A	A	B	B	A	A	A	A
C	A	B	A	A	E	B	A	A	A	A	A	A	C	A	A	A	A	D	B	A
B	A	A	A	C	B	A	B	A	A	B	C	A	A	A	B	A	A	D	C	C
C	A	B	B	C	B	B	A	A	D	C	A	B	B	A	B	A	A	C	B	A
C	D	A	A	A	A	A	C	A	B	A	C	A	B	D	A	A	D	A	B	A
A	A	B	B	A	D	B	B	A	A	B	A	A	D	C	D	C	B	A	B	A
D	C	A	A	A	A	A	A	A	A	A	A	A	D	B	E	A	A	B	A	A
B	A	A	A	A	A	A	A	C	B	B	A	B	B	D	A	A	A	A	B	A
B	A	A	C	B	A	A	B	A	C	B	A	E	B	A	A	A	A	A	A	A
C	A	A	A	B	A	B	A	B	A	B	A	B	B	A	C	B	B	B	B	B
A	B	B	D	A	A	C	A	A	A	A	A	B	B	B	D	A	A	A	A	C
C	C	A	B	A	B	A	C	B	C	C	B	D	A	A	B	A	A	A	A	

For order of occurrence read downwards; each column in succession.

TABLE 3 (a)

Fine finish lug holes - constant-amplitude fatigue test results (S_{min} = 23.4 MPa)*

Specimen number	Pin/hole clearance (mm) End 1	Pin/hole clearance (mm) End 2	Fatigue failure Cycles	Fatigue failure End	Fatigue crack classification (Fig. 9 (a))
S_{max} = 195 MPa (S_a = 86 MPa)					
BJ20FA	(clamped)	0.036	9,570	2	19,20,22,29
BJ17IA	0.025	0.025	11,000	2	20,27,32
CL23EA	0.025	0.025	12,300	1	5,13,32
CL24FA	0.023	0.023	13,400	2	3,19,22,29
log. average life = 11,480; s.d. log. life = 0.063					
S_{max} = 165 MPa (S_a = 71 MPa)					
BJ14BA	0.025	0.025	18,500	2	10,13,16,21
CL21IA	0.028	0.028	19,400	1	3,8,29,34
BJ11EA	0.025	0.025	20,940	2	5,14,32
log. average life = 19,590; s.d. log. life = 0.027					
S_{max} = 137 MPa (S_a = 57 MPa)					
BJ1DA	0.023	0.025	28,500	2	3,27,33
BJ15IA	0.023	0.023	35,900	2	6,27,33
CL22HA	0.036	0.028	37,260	2	28,33
CL27GA	0.025	0.028	37,700	2	4,13,33
log. average life = 34,620; s.d. log. life = 0.057					
S_{max} = 105 MPa (S_a = 41 MPa)					
BJ14FA	0.018	0.018	95,100	2	28,32
BJ19CA	0.025	0.025	100,610	2	5,14,32
CL24BA	0.028	0.025	105,500	1	15,33
log. average life = 100,300; s.d. log. life = 0.023					
S_{max} = 67 MPa (S_a = 21.8 MPa)					
BJ9GA	0.025	0.025	435,500	1	3,12,33
BJ12FA	0.020	0.023	515,900	2	13,33
CL25IA	0.028	0.028	564,200	2	12,33
CL22FA	0.020	0.018	1,080,500	1	6,14,33
log. average life = 608,300; s.d. log. life = 0.173					
S_{max} = 51 MPa (S_a = 13.8 MPa)					
BJ7CA	0.030	0.028	3,001,600	2	14,33
BJ16DA	0.025	0.023	3,763,400	1	13,32
log. average life = 3,361,000; s.d. log. life = 0.069					
S_{max} = 44 MPa (S_a = 10.4 MPa)					
BJ18FA	0.025	0.025	3,491,500	)	
BJ19EA	0.025	0.025	4,199,600	) Unbroken	

*Tests made at 1 Hz, except for two lowest stress levels when 3 to 4 Hz used.

TABLE 3 (b)
Coarse finish lug holes - constant-amplitude fatigue test results
(S_{min} = 23.4 MPa)*

Specimen number	Pin/hole clearance (mm) End 1	Pin/hole clearance (mm) End 2	Fatigue failure Cycles	Fatigue failure End	Fatigue crack classification (Fig. 9 (a))
S_{max} = 195 MPa (S_a = 86 MPa)					
BJ20FB	0.030	0.033	9,240	2	32
BJ17IB	0.023	0.023	14,300	1	4,26,32
CL23EB	0.023	0.023	16,830	1	22,28,30
CL24FB	0.023	0.028	17,600	1	20,26,33
log. average life = 14,070; s.d. log. life = 0.128					
S_{max} = 165 MPa (S_a = 71 MPa)					
CL21EB	0.023	0.025	23,900	2	6,24,32
BJ14BB	0.010	0.010	25,060	1	13,20,32
CL21IB	0.025	0.025	25,110	2	4,15,32
log. average life = 24,680; s.d. log. life = 0.012					
S_{max} = 137 MPa (S_a = 57 MPa)					
BJ14FB	0.025	0.025	40,200	2	19,28
BJ1DB	0.025	0.023	42,190	1	2,14,33
CL22HB	0.028	0.025	42,660	1	28,33
CL27GB	0.023	0.025	45,900	1	28,33
log. average life = 42,690; s.d. log. life = 0.024					
S_{max} = 105 MPa (S_a = 41 MPa)					
CL24BB	0.023	0.023	95,110	1	2,33
BJ19CB	0.025	0.020	102,800	1	15,33
CL26CB	0.076	0.061	111,700	2	3,15,32
log. average life = 102,980; s.d. log. life = 0.035					
S_{max} = 67 MPa (S_a = 21.8 MPa)					
BJ9GB	0.025	0.025	635,800	1	33,35
CL22FB	0.020	0.020	723,400	2	27,33
CL25IB	0.023	0.018	1,008,000	1	14,33
BJ12FB	0.018	0.048	1,172,000	2	27,32
log. average life = 858,600; s.d. log. life = 0.123					
S_{max} = 51 MPa (S_a = 13.8 MPa)					
BJ19EB	0.020	0.020	2,496,600	1	1,33
BJ18HB	0.028	0.025	2,997,000	1	20,33
log. average life = 2,735,000; s.d. log. life = 0.056					
S_{max} = 44 MPa (S_a = 10.4 MPa)					
BJ16DB	0.025	0.025	3,070,700	)	
BJ18FB	0.025	0.025	3,157,000	) Unbroken	

*Tests made at 1 Hz, except for two lowest stress levels when 3 to 4 Hz used.

TABLE 4
Lug hole surface finish - spectrum loading fatigue test results
(S_{min} = 23.4 MPa; S_{max} = 195 MPa)

Specimen number	Hole finish		Pin/hole clearance (mm) End 1	End 2	Fatigue failure Programmes	End	Fatigue crack classification (Fig. 9 (a))
Severe spectrum (programme loading)							
BJ20DA	F		0.023	0.028	182.5	1	24,32,43
CL25GA	F		0.030	0.030	217.4	1	25,34,43
BJ13IA	F		0.025	0.023	221.5	1	27,31,32,40
		(A)	log. average life = 206.4; s.d. log. life = 0.046				
BJ20DB	C		0.051	0.023	249.4	2	37,43
BJ13IB	C		0.023	0.023	264.5	1	14,19,27,32
CL25GB	C		0.025	0.025	305.5	1	9,27
		(B)	log. average life = 272.1; s.d. log. life = 0.045				
Moderate spectrum (programme loading)							
BJ2IA	F		0.025	0.025	690.5	1	25,34,43
CL26CA	F		0.023	0.025	707.5	2	2,33,43
BJ18HA	F		0.025	0.028	821.5	2	26,34,42
CL21EA	F		0.025	0.025	905.5	2	10,27,30,40
		(C)	log. average life = 776.4; s.d. log. life = 0.056				
BJ15IB	C		Not recorded		869.5	2	18,23,43
BJ7CB	C		0.030	0.023	870.5	1	12,44
BJ2IB	C		0.023	0.025	932.5	2	18,21,43
		(D)	log. average life = 890.4; s.d. log. life = 0.017				

Ratios of lives under Moderate and Severe spectra :

$$\frac{(C)}{(A)} = 3.76; \quad \frac{(D)}{(B)} = 3.27$$

TABLE 5
Lug frequency of cycling - constant-amplitude fatigue test results
(S_{min} = 23.4 MPa)

Specimen number	Pin/hole clearance (mm)		Cyclic freq. (Hz)	Fatigue failure		Fatigue crack classification (Fig. 9 (a))
	End 1	End 2		Cycles	End	
S_{max} = 195 MPa (S_a = 86 MPa)						
BJ13H3	0.025	0.025	1	13,440	2	17,21,22,27
CL28H4	0.033	0.033	1	13,700	2	3,22,29,34
CL29H3	0.025	0.025	1	14,000	1	28,33
CL29F2	0.015	0.018	1	14,300	1	5,15,32
log. average life = 13,860; s.d. log. life = 0.012						
BJ7E2	0.036	0.036	4	11,900	2	5,11,13,19
BJ15F4	0.033	0.033	4	12,900	2	4,8,15,34
BJ15D3	0.023	0.015	4	13,100	1	10,18,28
CL29H1	0.030	0.038	4	13,500	1	10,12,16,20
log. average life = 12,840; s.d. log. life = 0.023						
BJ6I4	0.033	0.033	16	11,700	1	8,19,28
BJ7G3	0.033	0.028	15.6	13,000	2	7,14,20,34
CL29J3	0.038	0.038	16	13,600	2	6,12,17
BJ10D4	0.030	0.036	16	16,300	1	5,13,22,31
log. average life = 13,550; s.d. log. life = 0.060						
S_{max} = 105 MPa (S_a = 41 MPa)						
BJ1C3	0.033	Not recorded	1	90,900	1	8,18,28
BJ13H4	0.025	0.020	1	94,100	1	28,33
BJ14E3	0.025	0.030	1	95,900	2	28,33
CL28I2	0.033	0.033	1	100,000	1	28,33
log. average life = 95,170; s.d. log. life = 0.017						
CL29J1	0.028	0.036	4.2	89,500	1	28,33
BJ7F2	0.038	0.038	4	91,500	1	5,11,13,19
BJ11B3	0.025	0.025	4	98,200	1	17,21,23,26
BJ10J3	0.023	0.043		103,400	2	28,32
log. average life = 95,490; s.d. log. life = 0.029						
BJ6B3	0.038	0.036	16	88,300	2	17,23,28
BJ15F3	0.033	0.036	16	103,700	2	3,8,29,34
CL29H4	0.028	0.025	15.6	115,300	2	2,8,18,29
BJ10C4	0.023	0.023	15.6	133,515	1	6,13,16,23
log. average life = 108,960; s.d. log. life = 0.076						

TABLE 5 (cont)
Lug frequency of cycling - constant-amplitude fatigue test results
(S_{min} = 23.4 MPa)

Specimen number	Pin/hole clearance (mm) End 1	Pin/hole clearance (mm) End 2	Cyclic freq. (Hz)	Fatigue failure Cycles	Fatigue failure End	Fatigue crack classification (Fig. 9 (a))
S_{max} = 67 MPa (S_a = 21.8 MPa)						
BJ11J2	0.036	0.033	1	590,900	1	1,36
BJ2F3	0.046	0.046	1	630,400	2	6,33
BJ11G3	0.033	0.030	1	823,600	2	4,33
BJ16C4	0.036	0.033	1	926,800	1	4,33
CL28G3	0.038	0.038	1	1,679,400	2	15,33
log. average life = 862,600; s.d. log. life = 0.181						
BJ9D2	0.030	0.025	4	556,000	2	4,12,33
BJ20G4	Not recorded		4	1,119,600	1	5,15,33
BJ9C3	0.028	0.030	4	1,332,100	1	6,11,15,19
log. average life = 939,500; s.d. log life = 0.201						
BJ14E4	0.023	0.025	16	768,900	1	29,33
BJ7G4	0.023	0.025	16	810,300	2	5,13,33
BJ4G2	0.033	0.033	16	890,300	1	28,36
BJ20G3	0.048	0.046	15.5	890,500	2	12,36
BJ13B3	Not recorded		15.5	893,400	2	12,36
log. average life = 849,100; s.d. log. life = 0.030						
S_{max} = 51 MPa (S_a = 13.8 MPa)						
BJ11G4	0.046	0.041	4	3,828,400	2	36
BJ17B4	Not recorded		4	4,240,600	1	5,12,36
CL29F3	Not recorded		4	4,526,800	2	4,14,36
log. average life = 4,188,700; s.d. log. life = 0.037						
BJ10DA	0.020	0.020	15.6	3,899,700	2	6,32
CL29J2	0.023	0.025	16	4,993,800	1	5,33
BJ9C4	0.043	0.046	15.5	7,835,300	2	3,15,33
log. average life = 5,343,700; s.d. log. life = 0.154						

TABLE 6
Lug frequency of cycling - spectrum loading fatigue test results
(S_{min} = 23.4 MPa; S_{max} = 195 MPa)

Specimen number	Pin/hole clearance (mm) End 1	Pin/hole clearance (mm) End 2	Cyclic freq. (Hz)	Fatigue failure Programmes	Fatigue failure End	Fatigue crack classification (Fig. 9 (a))
Severe spectrum (programme loading)						
BJ20C4	0.048	0.046	1	213.5	2	2,36,43
BJ6I3	0.038	0.041	1	218.5	1	10,26,43
BJ8F3	0.038	0.043	1	262.5	1	25,32,43
	(A) log. average life = 230.5; s.d. log. life = 0.049					
Severe spectrum (random loading)						
BJ19H4	0.036	0.043	1	184.6	1	24,32,43
BJ5J4	0.036	0.036	1	193.8	2	35,43
BJ12B3	0.025	0.041	1	199.8	2	26,36,43
	(B) log. average life = 192.6; s.d. log. life = 0.017					
Moderate spectrum (programme loading)						
BJ11B4	0.025	0.041	1	745.5	1	5,17,24,34,45
BJ9B2	0.043	0.043	1	775.5	1	17,24,36,44
BJ8F4	0.030	0.028	1	903.5	2	2,17,34,45
	(C) log. average life = 805.4; s.d. log. life = 0.044					
Moderate spectrum (random loading)						
BJ2F4	0.030	0.030	1	750.0	2	10,13,26,44
BJ10C3	Not recorded		1	819.0	1	11,21,44
BJ19D4	0.038	0.036	1	823.0	1	5,12,25,43
	(D) log. average life = 796.6; s.d. log. life = 0.023					

TABLE 6 (cont)
Lug frequency of cycling - spectrum loading fatigue test results
(S_{min} = 23.4 MPa; S_{max} = 195 MPa)

Specimen number	Pin/hole clearance (mm) End 1	End 2	Cyclic freq. (Hz)	Fatigue failure Programmes	End	Fatigue crack classification (Fig. 9 (a))
Severe spectrum (programme loading)						
BJ12I4	0.043	0.041	4	228.5	2	26,34,43
BJ6B4	0.036	0.038	4	236.5	1	11,27,43
BJ10J4	0.046	0.043	4	239.5	1	11,27,31,42
BJ16C3	Not recorded		4	249.5	1	25,34,43
	(E) log. average life = 238.4; s.d. log. life = 0.016					
Severe spectrum (random loading)						
BJ4E3	Not recorded		4	199.0	2	3,13,27,39
BJ12I3	Not recorded		4	201.8	2	26,36,43
BJ6C1	0.025	0.030	4	208.5	2	12,27,43
	(F) log. average life = 203.1; s.d. log. life = 0.010					
Severe spectrum (random loading - truncated)*						
BJ17F3	0.033	0.043	4	97.3	1	26,34,43
BJ6C2	0.033	0.041	4	105.5	2	27,34,43
BJ17B3	0.038	(clamped)	4	108.4	1	8,27,31,39
CL28H3	0.036	0.038	4	116.3	1	27,31,36,39
	(G) Ø (BJ) log. average life = 103.6; s.d. log. life = 0.024					
Moderate spectrum (programme loading)						
BJ9B1	0.043	0.041	4	772.5	1	8,21,27,31
BJ13B4	0.023	0.025	4	882.5	2	25,36,41
BJ20C3	0.036	0.046	4	885.5	2	26,34,43
	(H) log. average life = 845.2; s.d. log. life = 0.034					
Moderate spectrum (random loading)						
BJ7F1	0.051	0.041	4	675.0	1	11,26,31,38
BJ12B4	0.028	0.041	4	722.5	2	10,17,24,44
BJ5J3	0.043	0.025	4	729.0	2	3,5,36,41
BJ19H3	0.015	0.028	4	833.0	1	10,27,29
	(I) log. average life = 737.7; s.d. log. life = 0.038					
Moderate spectrum (random loading - truncated)*						
BJ9D1	0.041	0.036	4	383.6	2	9,20,27,30
BJ11J1	0.046	0.041	4	387.5	2	1,13,34,45
	(J) log. average life = 385.5; s.d. log. life = 0.003					

* By reducing load level 'F' to load level 'E'.

Ø Omitting CL38H3.

TABLE 6 (cont)
Lug frequency of cycling - spectrum loading fatigue test results
(S_{min} = 23.4 MPa; S_{max} = 195 MPa)

Specimen number	Pin/hole clearance (mm) End 1	End 2	Cyclic freq. (Hz)	Fatigue failure Programmes	End	Fatigue crack classification (Fig. 9 (a))
Severe spectrum (programme loading)						
BJ1C4	0.036	0.036	16	252.5	1	7,8,21,27,31
BJ17F4	0.033	0.033	16	261.5	1	1,13,34,44
BJ19D3	Not recorded		16	266.5	1	25,32,43
(K) (BJ) log. average life = 260.1; s.d. log. life = 0.012						
CL28G4	0.036	0.036	16	308.5	1	27,31,33,38
CL29H2	0.041	0.033	16	314.5	1	2,17,36,44
CL29F4	0.038	0.028	16	335.5	1	25,36,43
(CL) log. average life = 319.3; s.d. log. life = 0.019						
(BJ and CL) log. average life = 288.2; s.d. log. life = 0.051						
Moderate spectrum (programme loading						
BJ7E1	0.033	0.030	14.5	873.5	2	26,36,43
BJ4G1	Not recorded		16	958.5	2	2,13,34,44
BJ4E4	0.030	0.030	14.4	983.5	2	3,36,44
(L) (BJ) log. average life = 937.3; s.d. log. life = 0.027						
CL28I3	0.030	0.038	16	1071.5	1	26,34,43
CL29F1	0.038	0.043	16	1107.5	2	35,43
CL29J4	0.036	0.038	16	1129.5	2	26,34,43
(CL) log. average life = 1102.6; s.d. log. life = 0.012						
(BJ and CL) log. average life = 1016.6; s.d. log. life = 0.043						

Notes:

1. Programme loading lives denoted by xxx.5 programmes, and random loading lives by xxx.0 programmes indicate failure during the application of the peak load (level F) of the sequence.

2. Ratios of lives under the Moderate and Severe spectra are :

$$\frac{(C)}{(A)} = 3.49; \ \frac{(D)}{(B)} = 4.14; \ \frac{(H)}{(E)} = 3.55; \ \frac{(I)}{(F)} = 3.63; \ \frac{(L)}{(K)} = 3.60$$

TABLE 7
Lug frequency of cycling – summary of results under spectrum loading

Spectrum		Cyclic frequency (Hz) 1	4	16	Ratios
Severe	P/L	(A) 230.5 (0.049)	(E) 238.4 (0.016)	(K) 260.1 (0.012)	$\frac{(K)}{(E)} = 1.09$; $\frac{(K)}{(A)} = 1.13$
	R/L	(B) 192.6 (0.017)	(F) 203.1 (0.010)	-	$\frac{(E)}{(A)} = 1.03$; $\frac{(A)}{(B)} = 1.20$
		-	(G) (truncated) 103.6 (0.024)	-	$\frac{(E)}{(F)} = 1.17$
Moderate	P/L	(C) 805.4 (0.044)	(H) 845.2 (0.034)	(L) 937.3 (0.027)	$\frac{(L)}{(H)} = 1.11$; $\frac{(L)}{(C)} = 1.16$
	R/L	(D) 796.6 (0.023)	(I) 737.7 (0.038)	-	$\frac{(H)}{(C)} = 1.05$; $\frac{(C)}{(D)} = 1.01$
		-	(J) (truncated) 385.5 (0.003)	-	$\frac{(H)}{(I)} = 1.15$

Values given are log. average lives and standard deviations of log. life.

P/L = Programme Loading; R/L = Random Loading.

NSD = Not Significantly Different; SD = Significantly Different.

Comparisons of log. average lives in various groups :

(A) versus (B)	NSD	(I) versus (J)	SD
(C) versus (D)	NSD	(H) versus (C)	NSD
(E) versus (F)	SD	(I) versus (D)	NSD
(F) versus (G)	SD	(K) versus (E)	SD
(E) versus (A)	NSD	(K) versus (A)	NSD
(F) versus (B)	NSD	(L) versus (H)	NSD
(H) versus (I)	NSD	(L) versus (C)	NSD

TABLE 8
Estimated lives under different spectra

Stress range	Maximum stress (MPa)	Cycles to failure (N)	Cycles and (damage) per programme block of 1049 cycles			
			Severe spectrum		Moderate spectrum	
			Non-truncated	Truncated	Non-truncated	Truncated
F	195	13,122	1 (0.0000762)	-	1 (0.0000762)	-
E	165	21,988	112 (0.0050937)	113 (0.0051392)	28 (0.0012734)	29 (0.0013189)
D	137	38,445	248 (0.0064508)	248 (0.0064508)	62 (0.0016127)	62 (0.0016127)
C	105	100,324	314 (0.0031299)	314 (0.0031299)	138 (0.0013755)	138 (0.0013755)
B	67	813,195	304 (0.0003738)	304 (0.0003738)	320 (0.0003935)	320 (0.0003935)
A	51	3,959,791	70 (0.0000177)	70 (0.0000177)	500 (0.0001263)	500 (0.0001263)
Total damage per programme			0.0151421	0.0151114	0.0048576	0.0048269
Estimated life (programmes)			66	66	206	207

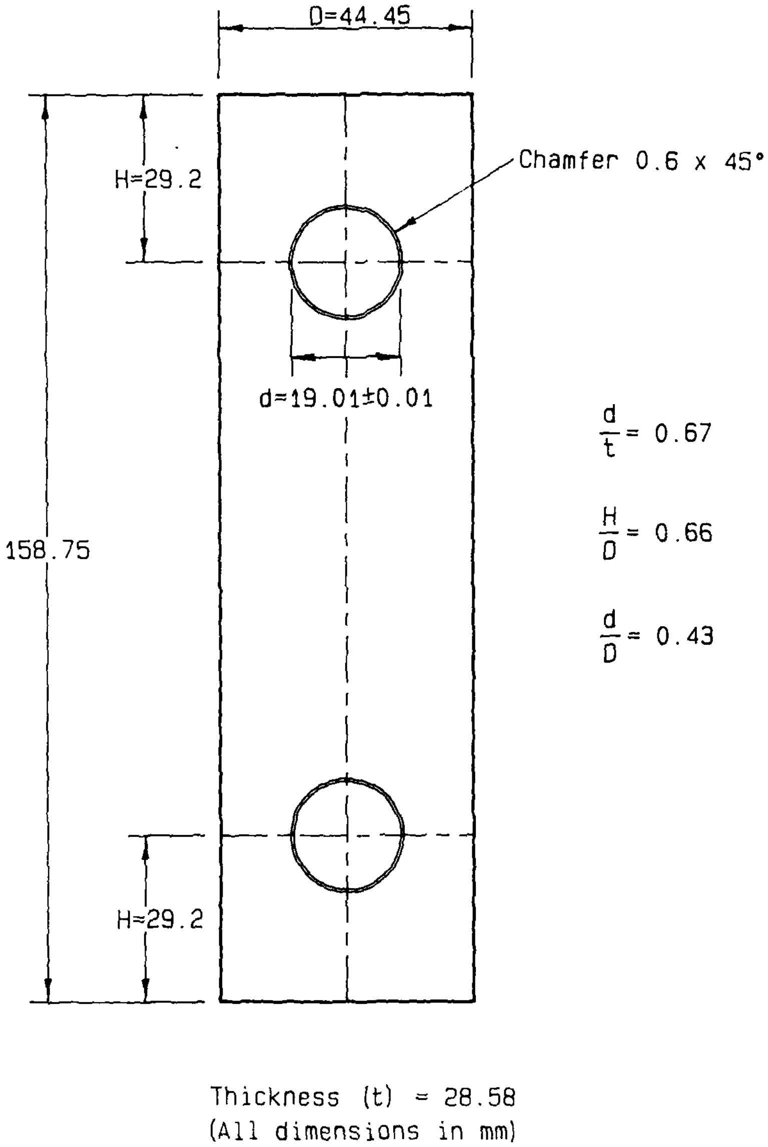


FIG. 1 LUG/PIN JOINT FATIGUE SPECIMEN

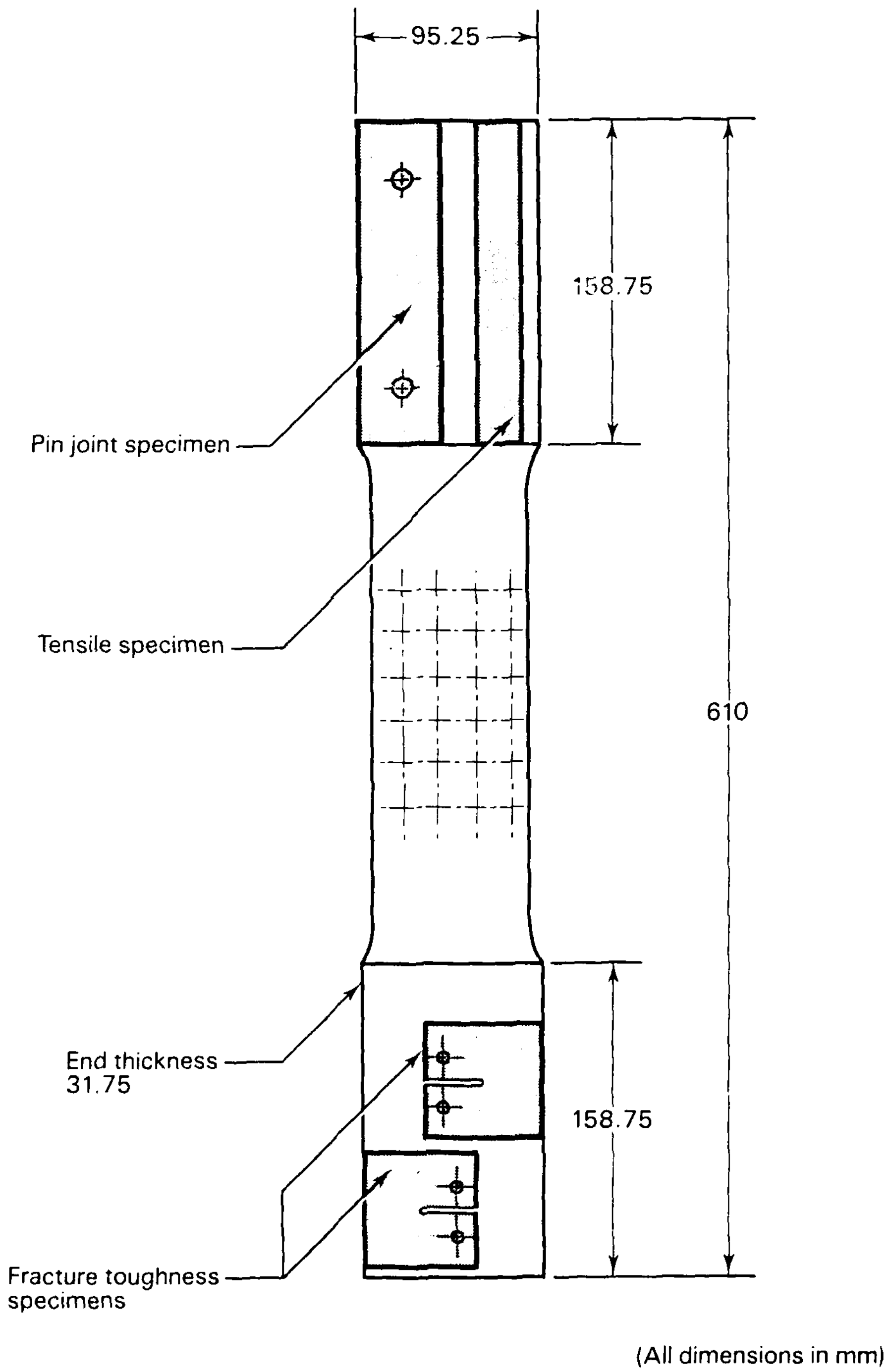
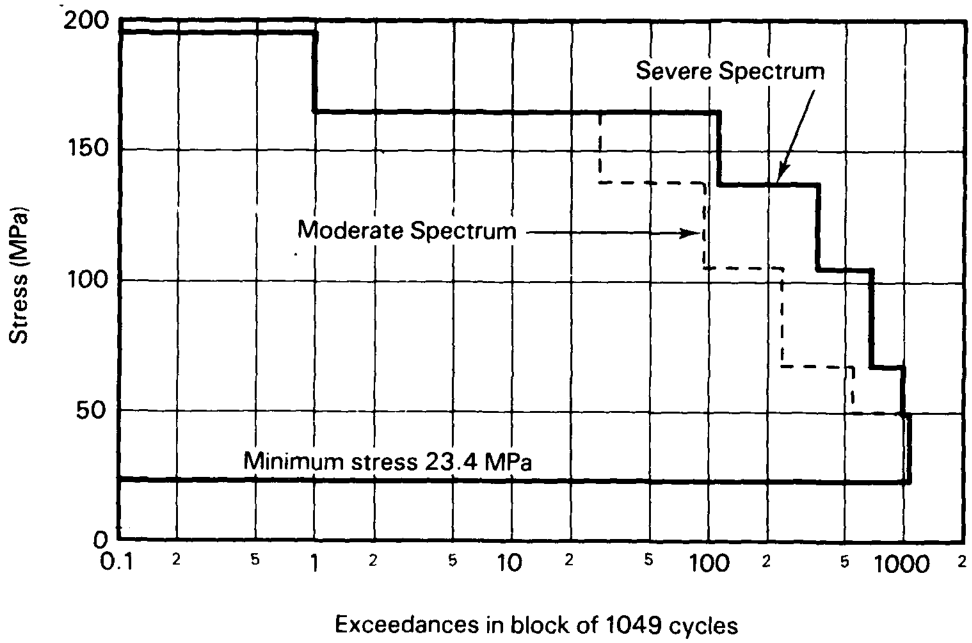


FIG. 2 LOCATION OF SPECIMENS CUT FROM LARGER FASTENER SPECIMENS (Ref. 37)

FIG. 3 SPECIMEN GRIPPING SYSTEM

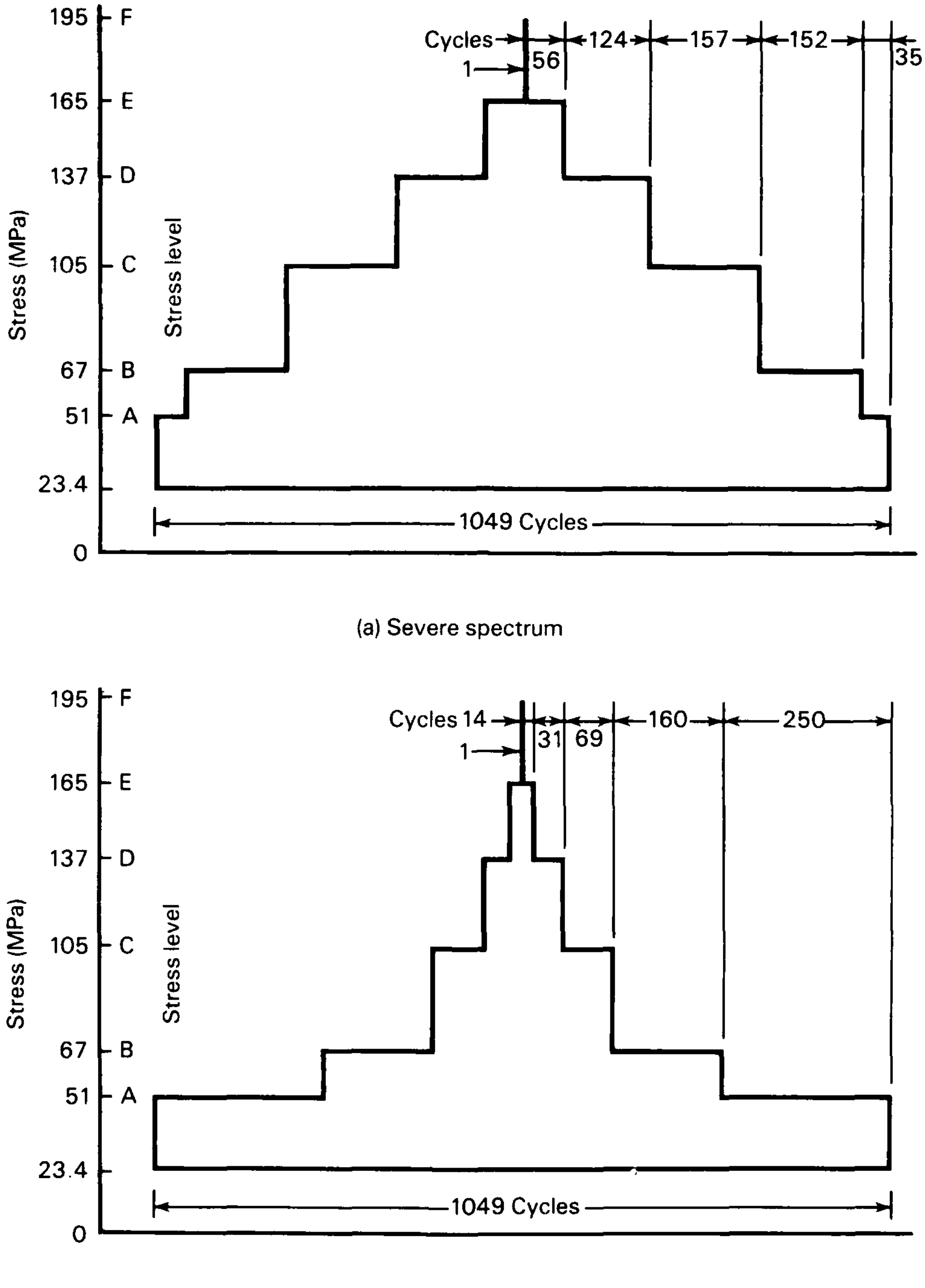


Stress level	Maximum stress (MPa)*	For block of 1049 cycles			
		Severe spectrum		Moderate spectrum	
		Cycles per load range	Cumulative frequency	Cycles per load range	Cumulative frequency
F	195	1	1	1	1
E	165	112	113	28	29
D	137	248	361	62	91
C	105	314	675	138	229
B	67	304	979	320	549
A	51	70	1049	500	1049

Minimum stress 23.4 MPa

* Based on nett area of specimen at lug

FIG. 4 STRESS SPECTRA



(a) Severe spectrum

(b) Moderate spectrum

FIG. 5 PROGRAMME LOAD SEQUENCES

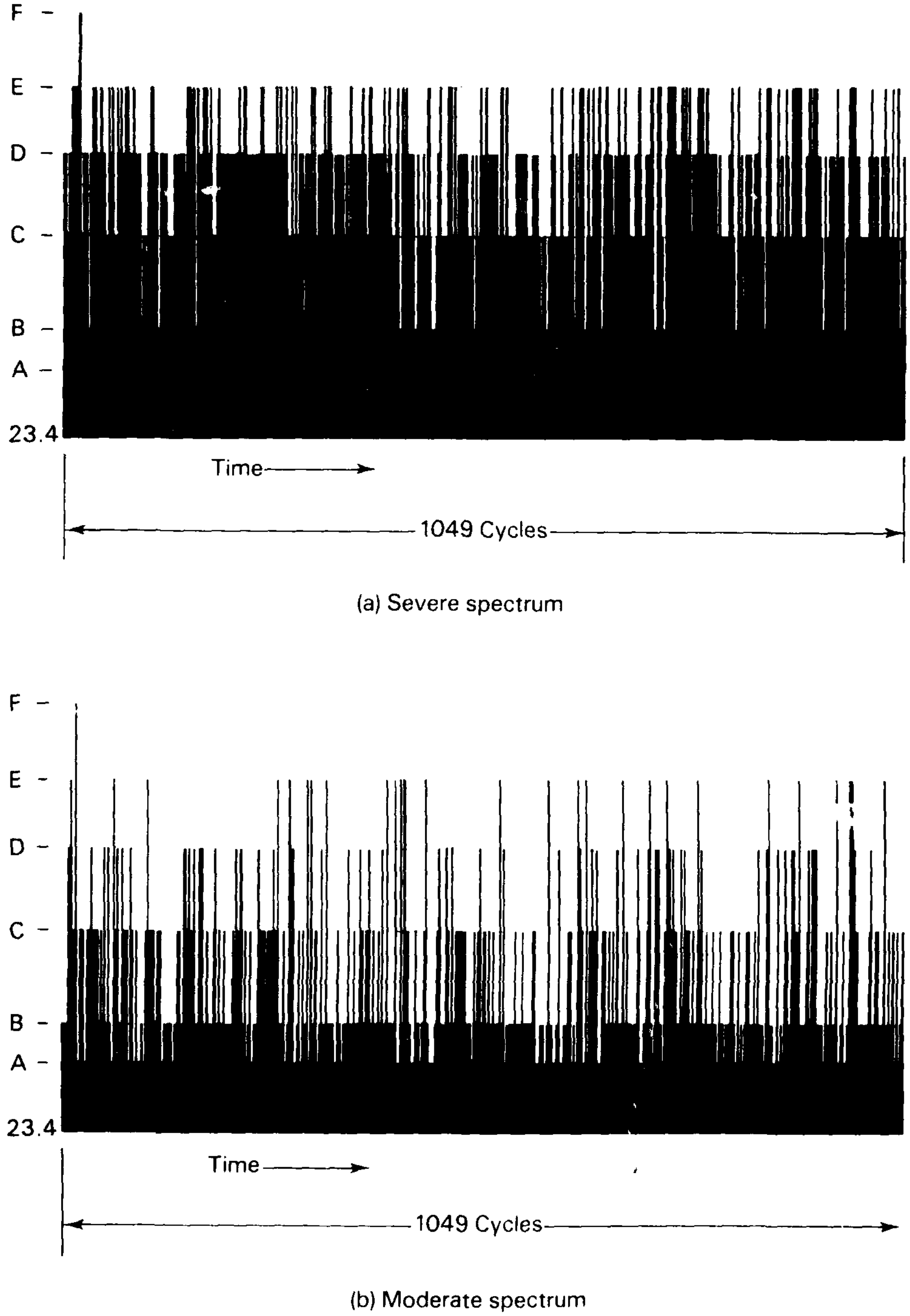


FIG. 6 PSEUDO-RANDOM LOAD SEQUENCES

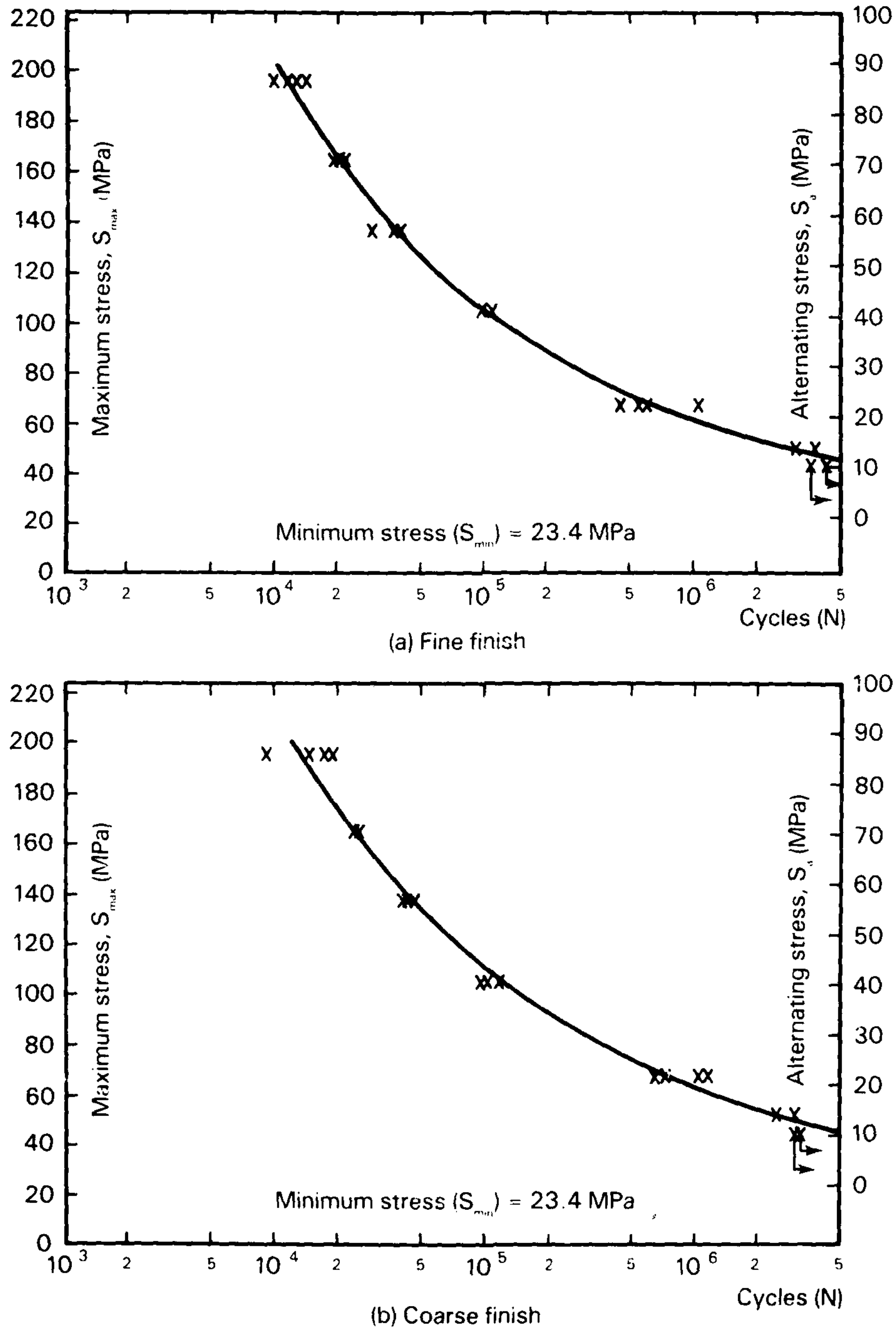
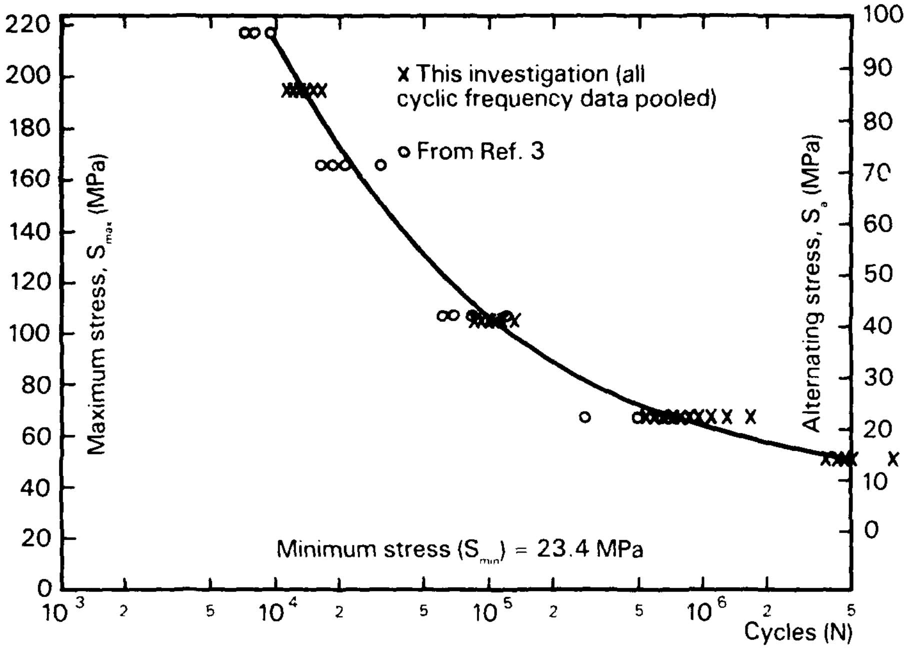
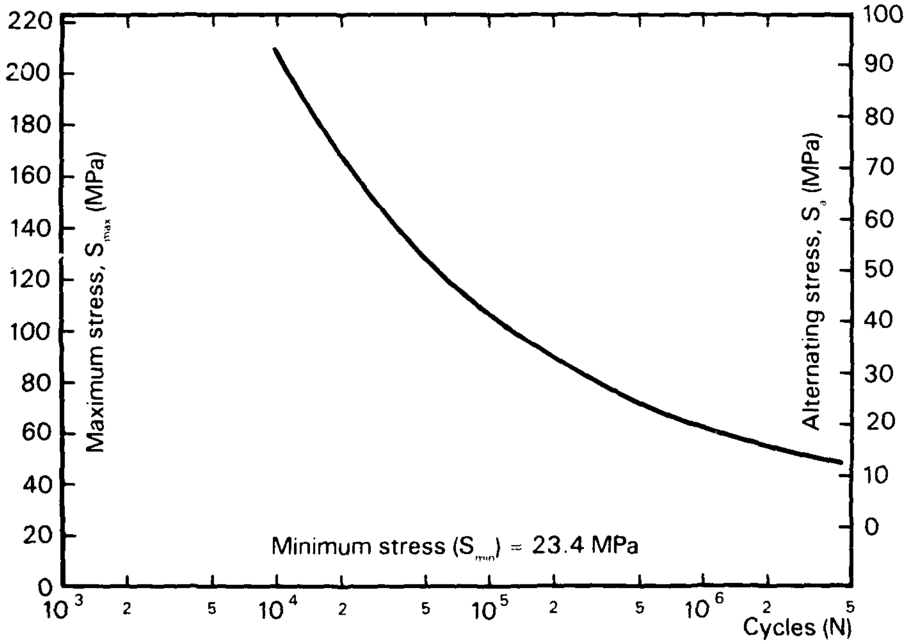


FIG. 7 SURFACE FINISH: CONSTANT – AMPLITUDE RESULTS

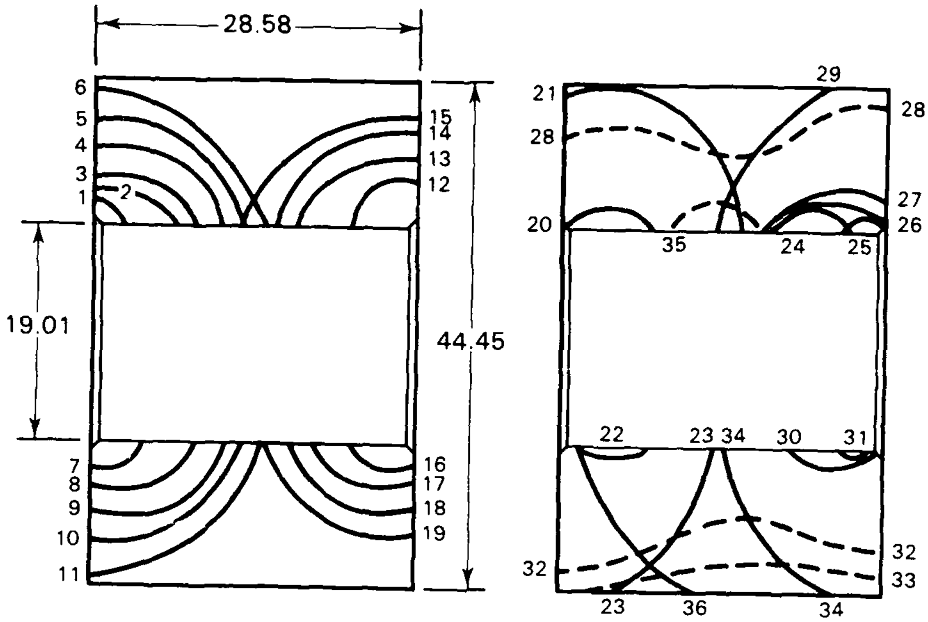


(a) Frequency of cycling (reamed holes) – constant-amplitude results

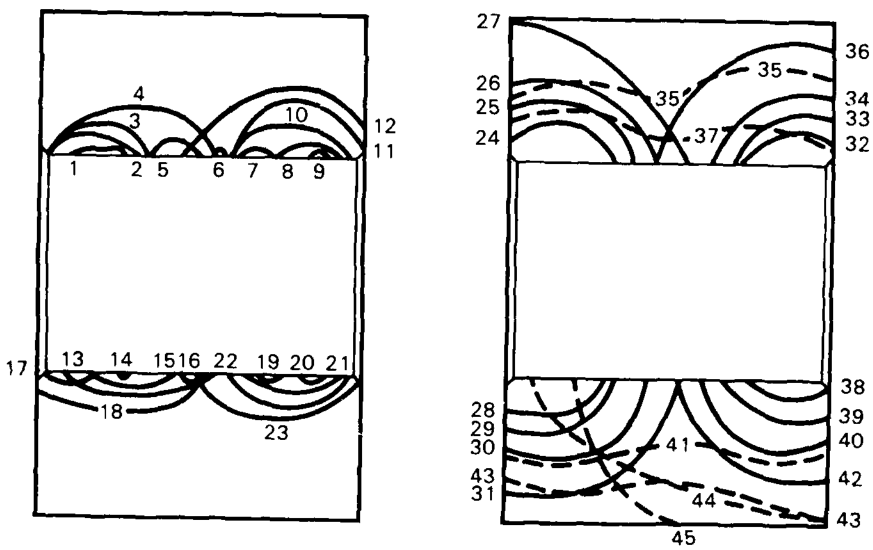


(b) Average S/N curve, pooled surface finish and frequency of cycling data

FIG. 8 POOLED CONSTANT – AMPLITUDE DATA



(a) Constant-amplitude



(b) Spectrum loading

FIG. 9 CLASSIFICATION SYSTEM FOR FATIGUE CRACKING

Note: Contours 9 and 25 in Fig. 9(a) and 4, 6, 15, 16, 27 and 28 in Fig. 9(b) Were not identified in this investigation.

(a) Non-truncated BJ12B4

(b) Truncated BJ11J1

FIG. 10 FRACTURE SURFACES OF TWO SPECIMENS TESTED UNDER THE MODERATE, PSEUDO-RANDOM SEQUENCE – MAGNIFICATION 2X.

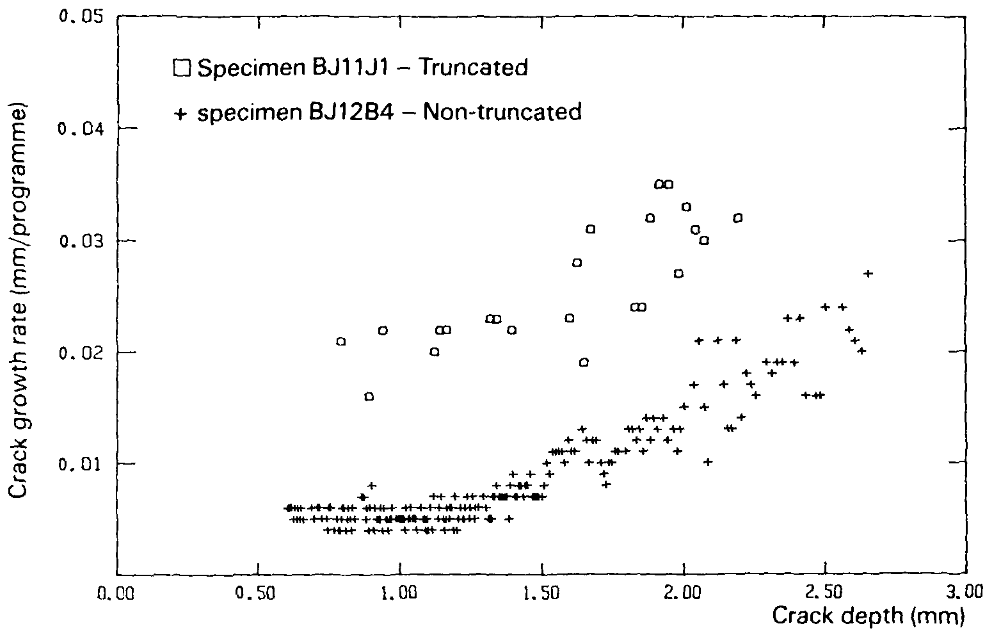


FIG. 11 CRACK GROWTH RATE AS A FUNCTION OF CRACK DEPTH

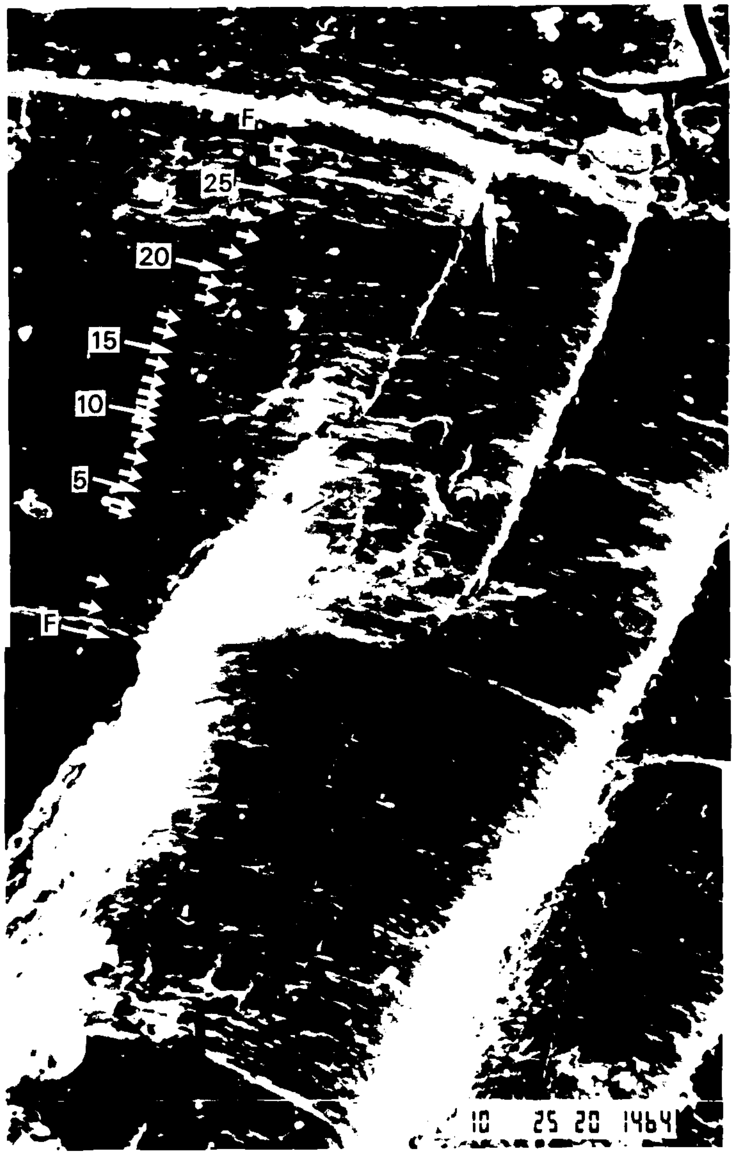


FIG. 12(a) SEM FRACTOGRAPH, NON-TRUNCATED SPECIMEN BJ12B4 – magnification 800X. (A single programme is shown bounded by the large striations produced by the once-per-block 195MPa stress – labelled F. The striations produced by the 28 applications of the 165 MPa stress are also indicated)

FIG. 12(b) SEM FRACTOGRAPH, TRUNCATED SPECIMEN BJ11J1 – magnification 550X. (A single programme is shown bounded by the striations produced by the once per block truncated stress labelled F(t). The striations produced by the other 28 applications of the 165 MPa stress are also indicated)

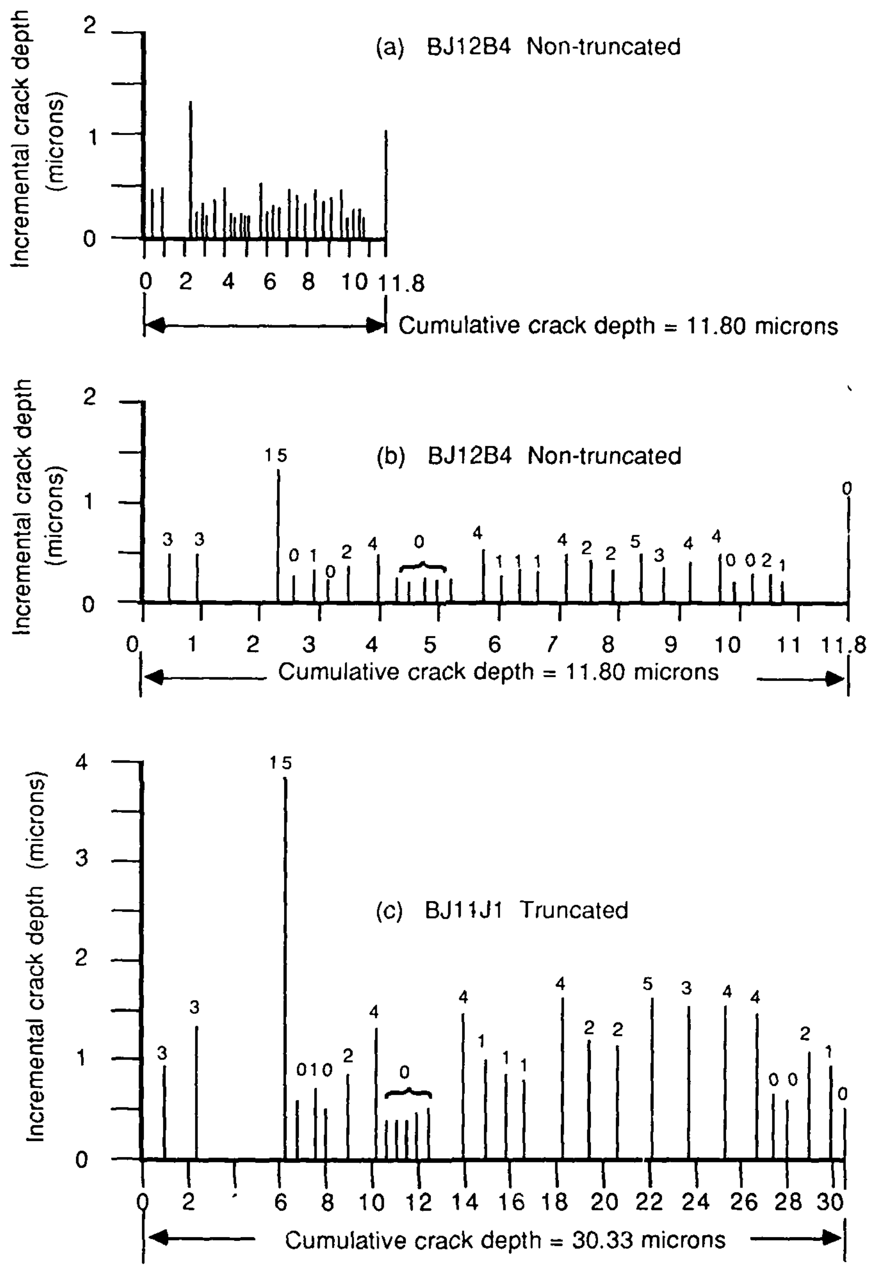


FIG. 13 MODERATE SPECTRUM. INCREMENTAL CRACK GROWTH PRODUCED BY EACH APPLICATION OF THE 165 MPa STRESS (E) AND THE PRECEDING LESSER STRESSES, AT A CRACK DEPTH OF APPROXIMATELY 2mm. (The numbers of 137 MPa stress (D) applied between each 165 MPa stress are shown above each bar)

FIG. 14 FATIGUE CRACK INITIATION AT INTER-METALLIC PARTICLES, SPECIMEN BJ151B – MAGNIFICATION 650X.

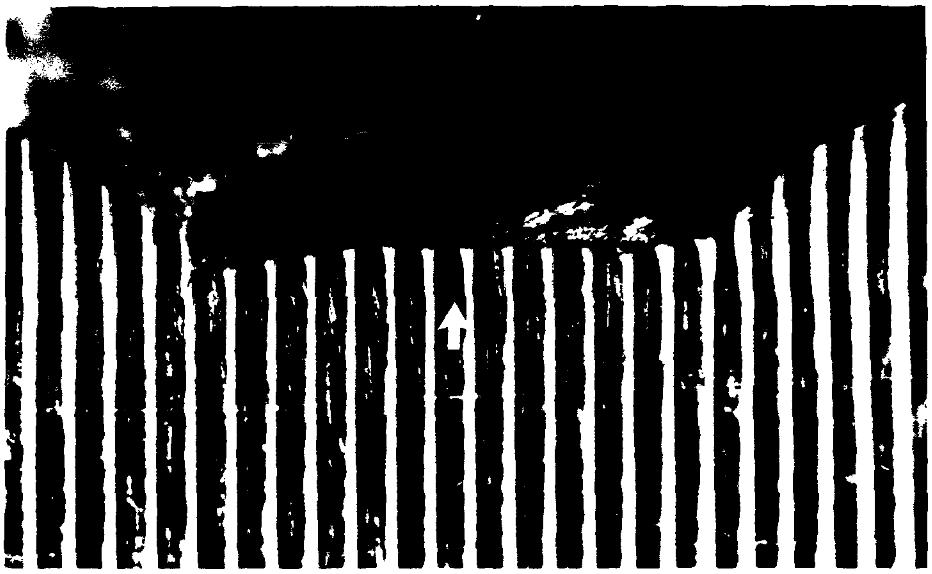


FIG. 15 HOLE SURFACE FINISH IN REGION OF THE LARGEST CRACK ON FRETTED SIDE OF SPECIMEN BJ20DB – MAGNIFICATION 23X.

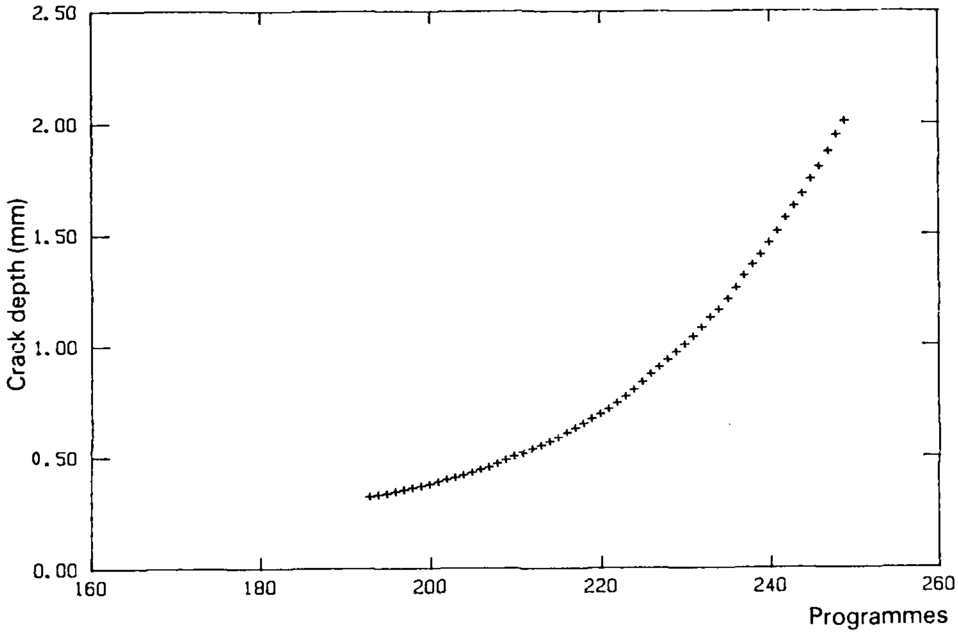


FIG. 16 FATIGUE CRACK GROWTH CURVE FOR CRACK INITIATED BY FRETTING IN SPECIMEN BJ20DB

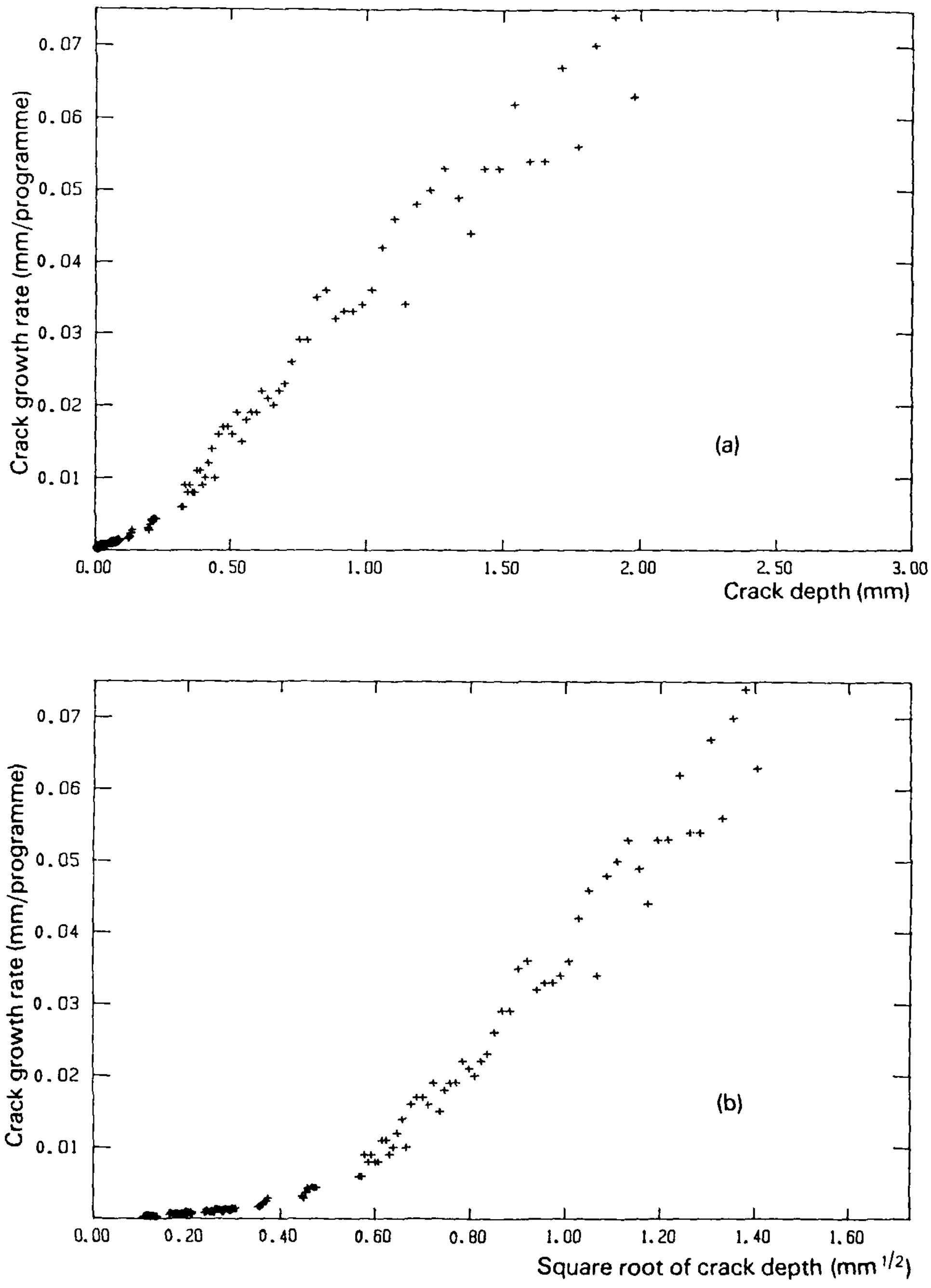


FIG. 17 (a) AND (b) CRACK GROWTH RATE AS A FUNCTION OF CRACK DEPTH.
(Specimen BJ20DB, crack initiated by fretting)

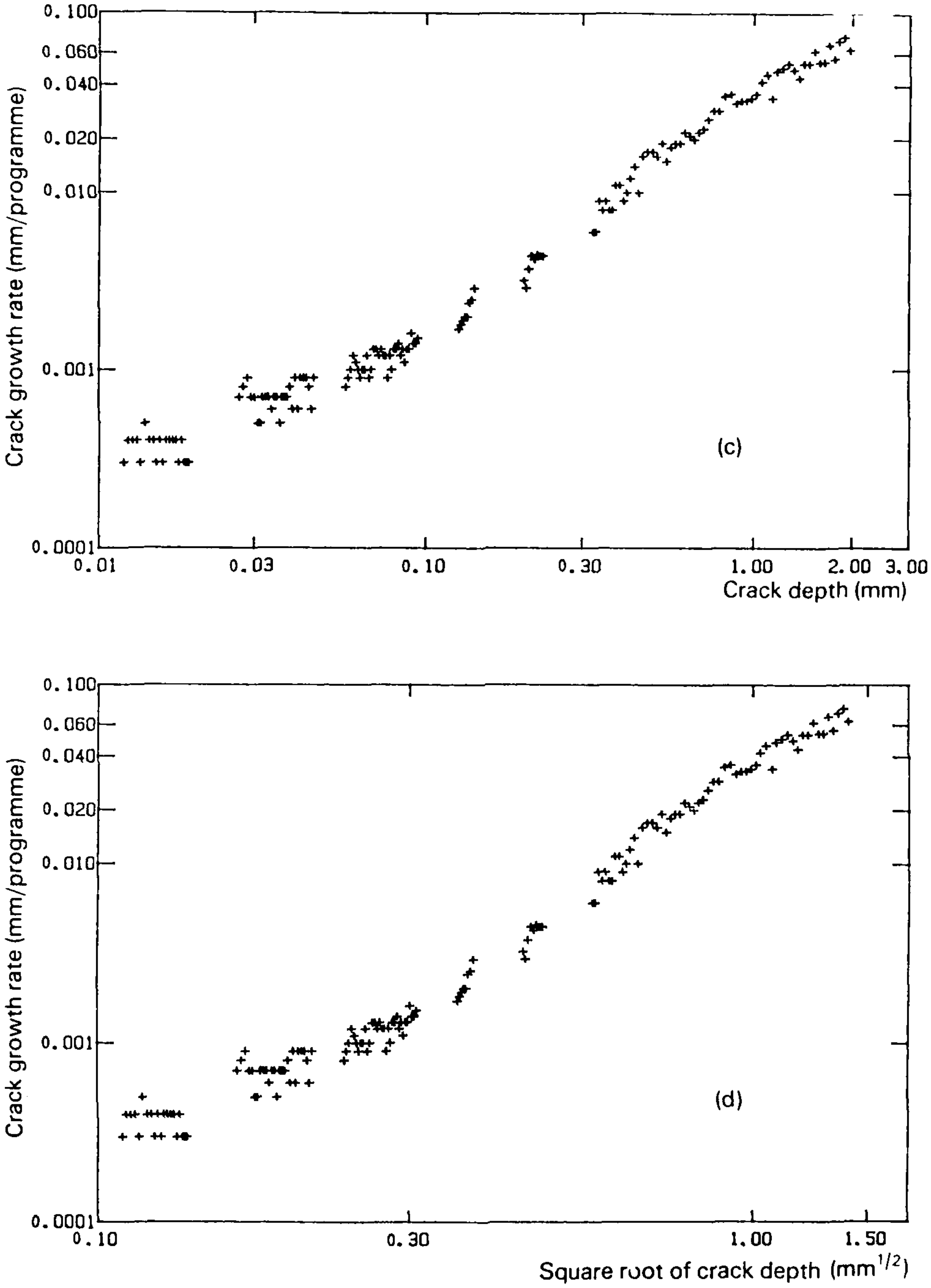
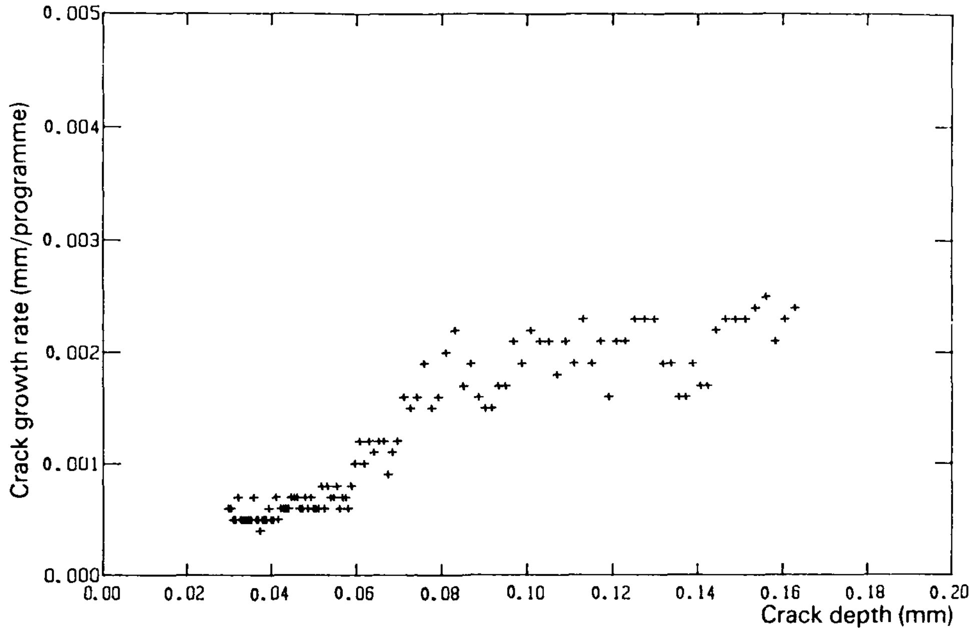
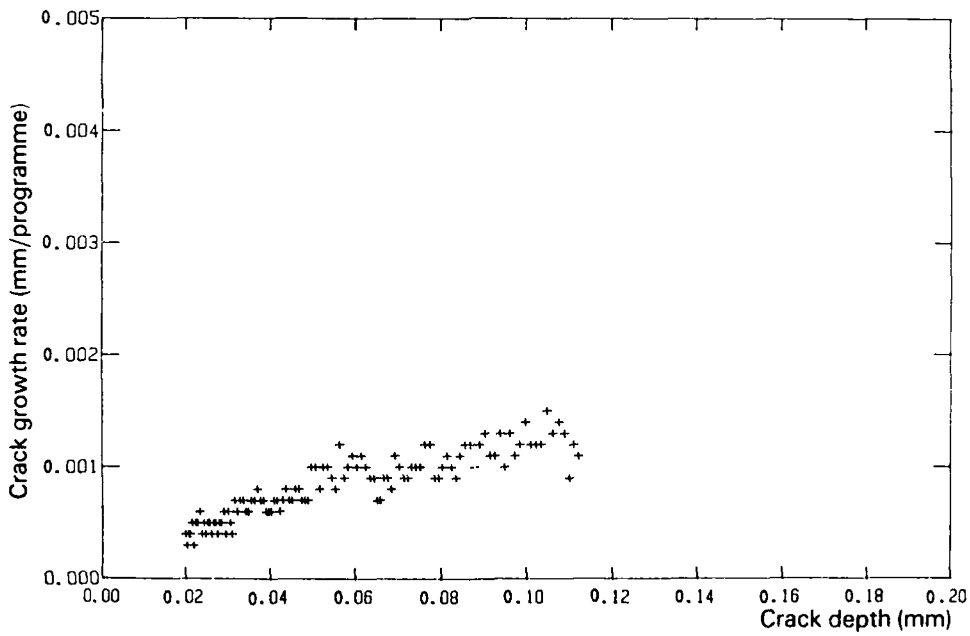


FIG. 17 (c) AND (d) CRACK GROWTH RATE AS A FUNCTION OF CRACK DEPTH.
(Specimen BJ20DB, crack initi[illegible]ed by fretting)



(a) Intermetallic particle no. 1



(b) Intermetallic particle no. 2

FIG. 18 CRACK GROWTH RATE AS A FUNCTION OF CRACK DEPTH. (Specimen BJ20DB, cracks initiated at intermetallic particles at machining grooves)

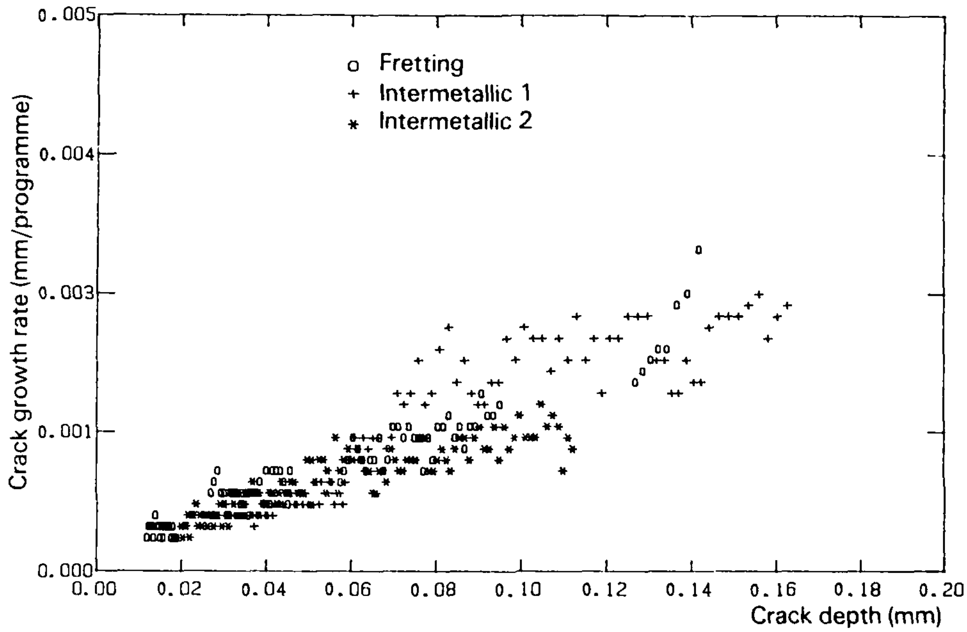
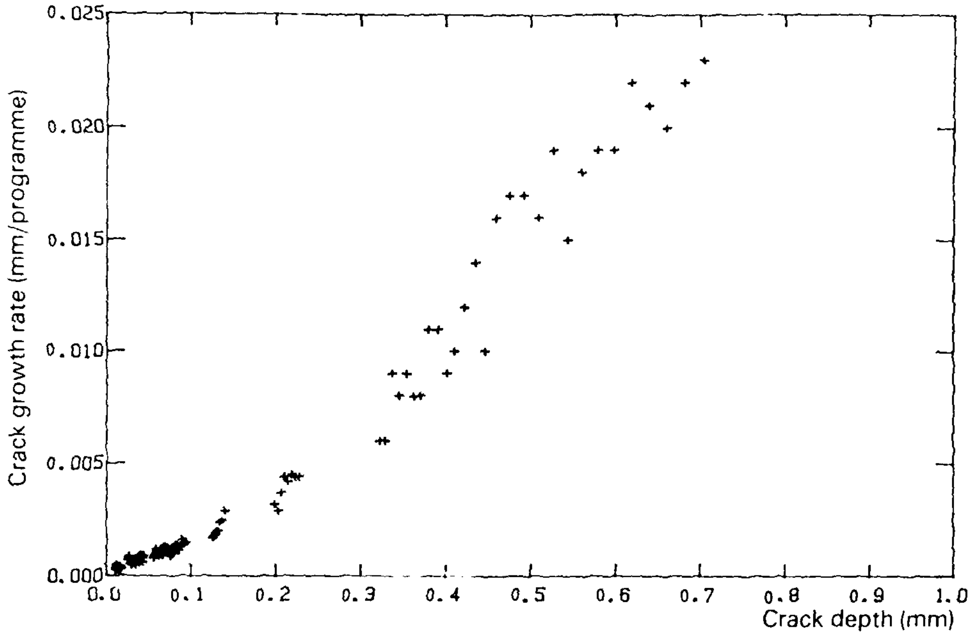
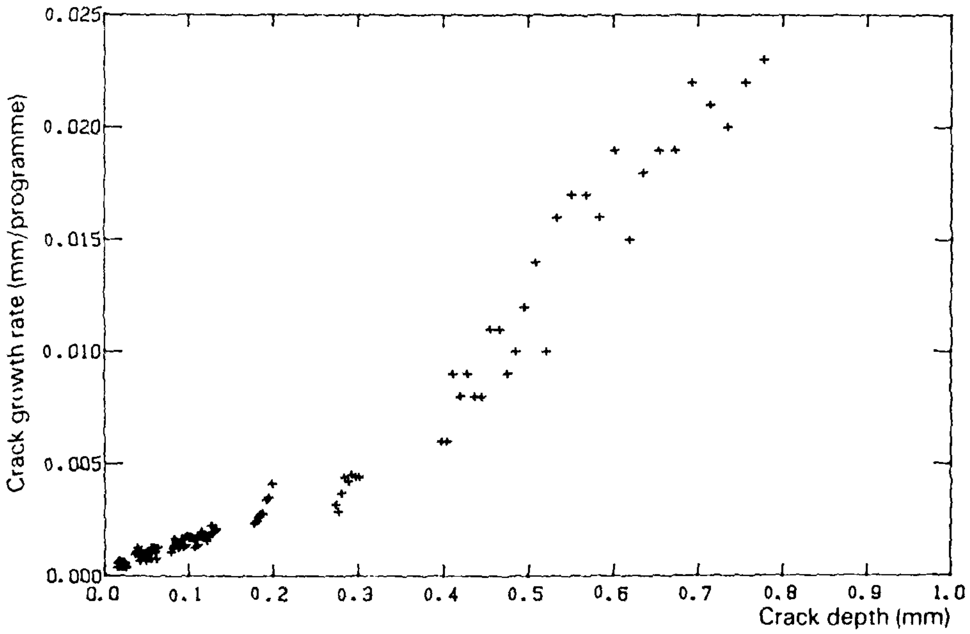


FIG. 19 FATIGUE CRACK GROWTH RATE AS A FUNCTION OF CRACK DEPTH OVER THE SMALL CRACK REGION

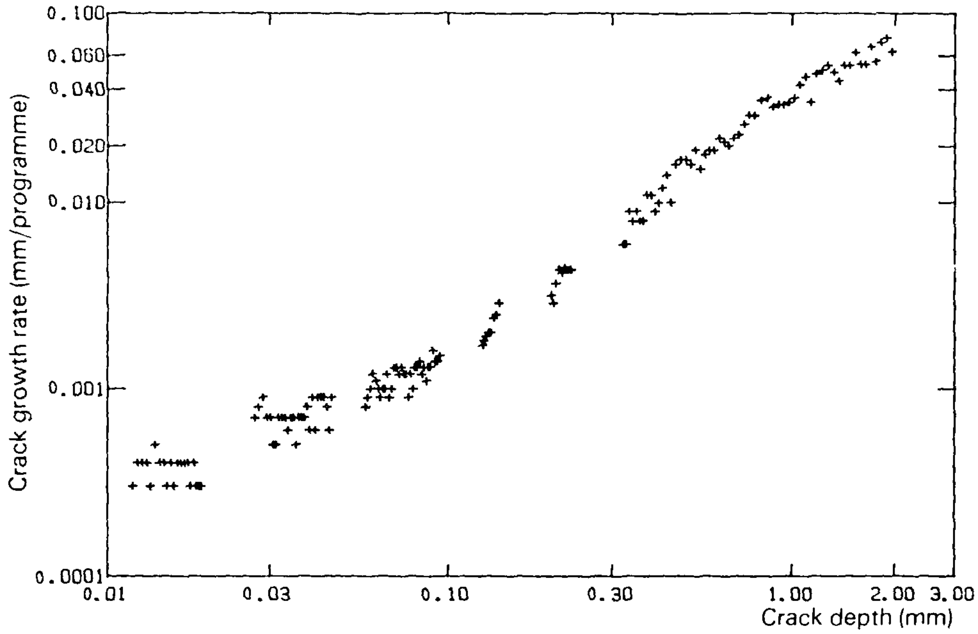


(a) Non-corrected data

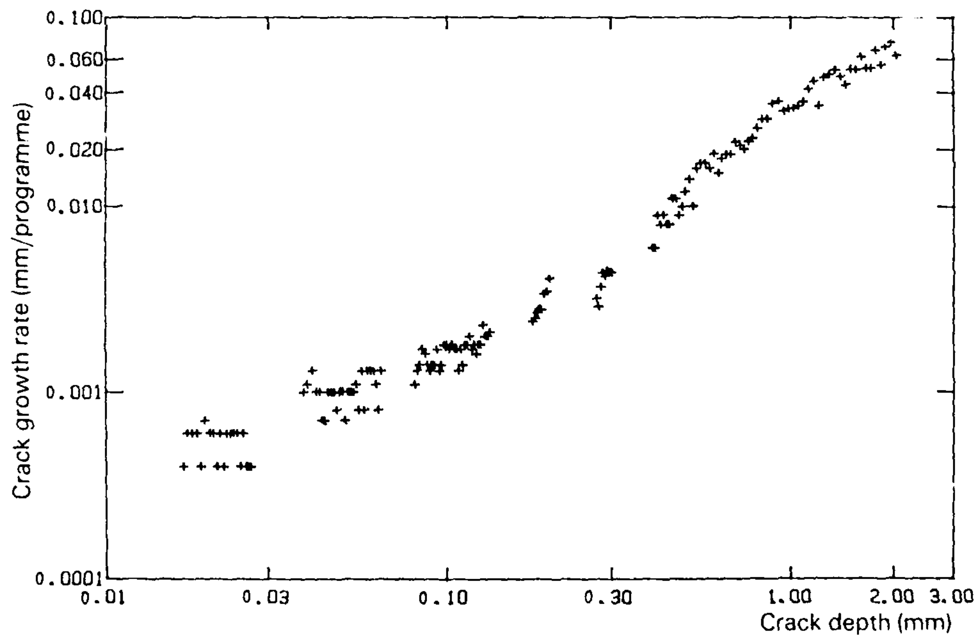


(b) Data corrected for optical foreshortening

FIG. 20 CRACK GROWTH RATE AS A FUNCTION OF CRACK DEPTH WITH CORRECTION FOR FORESHORTENING – LINEAR SCALES. (Specimen BJ20DB, crack initiated by fretting)



(c) Non-corrected data



(d) Data corrected for optical foreshortening

FIG. 20 CRACK GROWTH RATE AS A FUNCTION OF CRACK DEPTH WITH CORRECTION FOR FORESHORTENING – LOGARITHMIC SCALES (Specimen BJ20DB, crack initiated by fretting)

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Aluminum alloys	Loads (forces)
Cracking (fracturing)	Pin-loaded lugs
Cyclic rate	Spectrum loading
Fatigue (materials)	Surface finishing
Fatigue Tests	Truncation

15. DRDA SUBJECT CATEGORIES
0051C
0071N
0094G

16. ABSTRACT

An extensive series of tests has been carried out on thick (29 mm) clearance-fit pin joints of 2L.65 aluminium alloy. It was found that lug holes having a fine surface finish (1.9 microns) did not have fatigue lives greater than those with a coarse finish (27 microns), under either constant-amplitude or multi-load-level fatigue loading sequences. Thus, unless needed for other functional reasons, it may not be necessary to specify fine circumferential surface finishes in situations where fretting fatigue is likely to be a problem.

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16. ABSTRACT (CONT.)

Within the range 1 Hz to 16 Hz, frequency of cycling had no significant effect on the lives to failure under constant-amplitude and multi-load-level sequences. For each of two severities of spectrum adopted there were essentially no significant differences in fatigue lives under programme and pseudo-random loading sequences. Truncation of the once-per-block peak load resulted in significant reductions in life under both spectra. Detailed fractographic studies suggested that the size of the plastic zone caused by the peak load was greater than the extent of fatigue crack propagation within a block.

Fractographic examination of small fatigue cracks initiated either at intermetallics or by fretting showed no evidence of early rapid crack growth associated with the 'short-crack' effect.

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